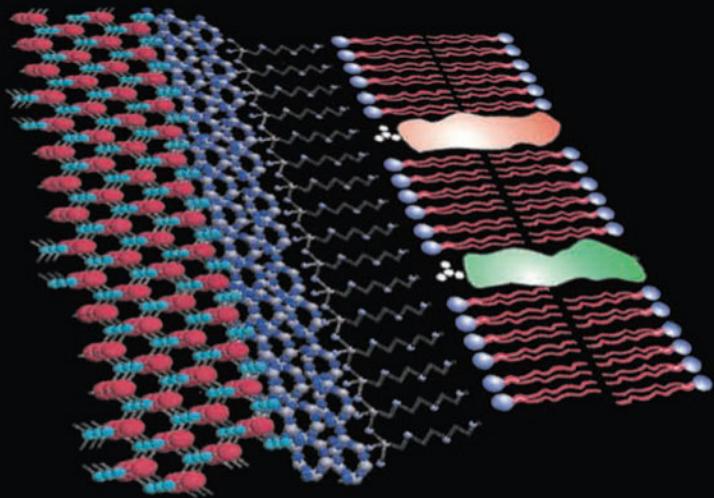


Manufacturing at the Nanoscale

Report of the National Nanotechnology Initiative Workshops
2002–2004



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About the Nanoscale Science, Engineering, and Technology Subcommittee

The Nanoscale Science, Engineering, and Technology (NSET) Subcommittee is the interagency body responsible for coordinating, planning, implementing, and reviewing the National Nanotechnology Initiative (NNI). NSET is a subcommittee of the National Science and Technology Council (NSTC), which is one of the principal means by which the President coordinates science, space, and technology policies across the Federal Government. The National Nanotechnology Coordination Office (NNCO) provides technical and administrative support to the NSET Subcommittee and supports the subcommittee in the preparation of multiagency planning, budget, and assessment documents, including this report.

For more information on the NSET Subcommittee, see <http://www.nano.gov/html/about/nsetmembers.html>.

For more information on NSTC, see <http://www.ostp.gov/nstc/>.

For more information on the NNI, NSET, and NNCO, see <http://www.nano.gov>.

About this document

The report is based on a series of NNI workshops held between 2002 and 2004 intended to solicit input from the research community as part of the ongoing NNI strategic planning activity. Several of these workshops addressed the NNI research agenda related to one of the original NNI “grand challenge” topics, “Manufacturing at the Nanoscale.” The findings and recommendations from these workshops were used as input for the NNI Strategic Plan released in December 2004, in particular the Program Component Area on Nanomanufacturing set out in that plan. The meetings were jointly sponsored by the National Science Foundation, and, through the NNCO, the other member agencies of the NSET Subcommittee.

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Front cover: Artist’s rendition of interface between semiconductor and SiO₂ layers (left side of image) and the self-assembled hydrophilic and membrane phospholipid layers for a biocavity laser (image courtesy of P. Gourley, Sandia National Laboratory).

Back cover: The Millipede project by IBM (artist’s rendition) uses cantilevers with nanometer-sized tips to create 10-nm-diameter indentations in a thermoplastic film for data storage. Storage densities greater than a terabit per square inch have been shown to be feasible using this approach (image courtesy of IBM Zurich Research Laboratory; unauthorized use not permitted).

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Manufacturing at the Nanoscale

National Nanotechnology Initiative Workshop Report

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Thanks are due to the principal authors and editors of this report, who are listed above on the title page. This report is based on a series of workshops (listed in Appendix D) conducted between 2002 and 2004 under the auspices of the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC). The sponsors wish to thank all the participants at those workshops, and in particular the organizers and participants of the May 13, 2002 workshop held at the National Science Foundation (see agenda, Appendix A), which provided the foundation for this report. Credit is due to the many distinguished scientists and engineers (listed below) who contributed to or reviewed this report after the workshop.

Thanks are also due to members of the NNCO staff who organized this NNI workshop series, and to Geoff Holdridge, Ron Bramlett, and other staff members from NNCO and WTEC, Inc. who assisted in final editing and production of the report. Special thanks are due to Pat Johnson for her editing work on the report. Finally, thanks to all the members of the NSET Subcommittee, who sponsored this series of workshops (through the NNCO) and reviewed the draft report before publication.

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PREFACE

This report on nanomanufacturing is the result of a series of workshops convened between 2002 and 2004 by the Nanoscale Science, Engineering, and Technology (NSET) Subcommittee of the National Science and Technology Council's Committee on Technology. The workshops were part of the NSET Subcommittee's long-range planning effort for the National Nanotechnology Initiative (NNI), the multiagency Federal nanotechnology program. The NNI is driven by long-term goals based on broad community input, in part received through these workshops. The NNI seeks to accelerate the research, development, and deployment of nanotechnology to address national needs, enhance our Nation's economy, and improve the quality of life in the United States and around the world, through coordination of activities and programs across the Federal Government. The NNI plays a critical role in supporting a balanced investment intended to help realize the true promise of nanoscale science and engineering and promote the responsible development of nanotechnology.

At each of the topical workshops, nanotechnology experts from industry, academia, and government were asked to develop broad, long-term (ten years or longer), visionary goals and to identify scientific and technological barriers that once overcome will enable advances toward those goals. The reports resulting from this series of workshops inform the respective professional communities, as well as various organizations that have responsibilities for coordinating, implementing, and guiding the NNI. The reports also provide direction to researchers and program managers in specific areas of nanotechnology research and development (R&D) regarding long-term goals and research needs.

Several of the 2002–2004 NNI workshops covered issues relevant to nanomanufacturing; these are listed in Appendix D. The workshop that provided the starting point for the drafting of this report was held at the National Science Foundation (NSF) on May 13, 2002. The purpose of this workshop was to seek input from the research community on the NNI research agenda related to one of the original NNI “grand challenge” topics, “Manufacturing at the Nanoscale.” The findings from this series of workshops were used in formulating the NNI Strategic Plan released in December 2004, particularly the Program Component Area (PCA) on Nanomanufacturing, and helped motivate one of the four overall NNI goals set out in that plan, “facilitate transfer of new technologies into products for economic growth, jobs, and other public benefit.” This report also provided input to the development of programs that make up portions of the fiscal years 2005–2007 NNI budgets requested for the NNI participating agencies, and will continue to inform the NNI research program under the Nanomanufacturing PCA.

This report will provide direction to researchers and program managers involved in nanomanufacturing R&D regarding long-term goals and research opportunities. The report identifies current scientific and technological advances, the research needs and goals for four generations of nanomanufactured products, the required scientific and technological infrastructure, the investment and implementation strategies for future nanomanufacturing R&D, and the relevant challenge areas and priorities for the next decade.

On behalf of the NSET Subcommittee, we wish to thank Drs. Julie Chen, Kevin Lyons, and Haris Doumanidis, who have served as NSF Program Directors for Nanomanufacturing, for their efforts in conducting these workshops and in preparing this report. We also thank all the workshop participants for their time, hard work, and contributions to this report. Their generous sharing of research results and insights ensures that this document will serve as a valuable reference for the NNI.

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EXECUTIVE SUMMARY

A series of workshops held from 2002 through 2004 have led to this report on the vision, advances, future directions, and strategic priorities for advancing manufacturing at the nanoscale. Nanomanufacturing is widely recognized as critical to realizing practical applications of nanotechnology in areas such as nanostructured materials, nanoelectronics, nanobiotechnology, and chemical/biological/radiological/explosives detection and protection. While exciting scientific discoveries in nanoscience evolve, there is a need for concomitant discoveries in engineering, and specifically in manufacturing, in order to transition from knowledge to products that benefit society. To achieve manufacturing at the nanoscale, the various branches of science and engineering must come together, integrating understanding of surface chemistry, electrostatics, fluid flow, adhesion, etc., to control the assembly and incorporation of nanoscale elements into micro- and macroscale products. This report focuses on the potential for and the barriers to high-volume, high-rate nanomanufacturing, with a primary emphasis on creation of new, broadly applicable processes, rather than on specific devices or structures. Industrial areas of relevance include, but are not limited to: *advanced materials; electronics, photonics, magnetics and related information and communications technologies; power, energy, and environmental remediation; chemicals/petrochemicals; pharmaceuticals, biochemicals, and food; medicine, health, and safety; aerospace, automotive, and appliance applications; and related services.*

CURRENT ADVANCES

Initial funding by the National Nanotechnology Initiative (NNI) has led to significant nanomanufacturing-related advances. This includes synthesis and processing of nanoelements or nanoscale building blocks such as nanotubes, nanoparticles, nanofibers, and quantum dots; nanotube dispersion in nanocomposites and atomic-layer deposition for nanoelectronics; patterning and templating of polymeric and biomolecular systems; directed assembly of two-dimensional (2D) and three-dimensional (3D) structures and devices; positioning, imaging, and measurement at nanoscale resolution; and modeling and simulation of material-energy interactions and manufacturing processes at the nano, micro, meso, and macro scales.

The capabilities of nanotechnology for systematic control and manufacture at the nanoscale have been categorized as evolving in four overlapping generations of nanotechnology products, each with different areas of R&D focus:

- *First generation* (beginning around 2000): passive (steady function) nanostructures, illustrated by nanostructured coatings, nanoparticles, nanowires, and bulk nanostructured materials.
- *Second generation* (beginning around 2005): active (evolving function) nanostructures, illustrated by transistors, amplifiers, targeted drugs and chemicals, sensors, actuators, and adaptive structures.
- *Third generation* (beginning around 2010): three-dimensional nanosystems and systems of nanosystems using various synthesis and assembly techniques such as bio-assembly, nanoscale robotics, networking at the nanoscale, and multiscale architectures.
- *Fourth generation* (beginning around 2015): heterogeneous molecular nanosystems, where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices, and fundamentally new functions will emerge from their engineered structures and architectures.

Much of what has already reached the marketplace is in the form of “first-generation” passive nanostructured products and nanotechnology-enabled manufacturing processes. Today research and development (R&D) is underway on “second-generation” products, and embryonic “third-generation” products are in the pipeline.

FUTURE DIRECTIONS/RESEARCH GOALS

Issues that remain for nanomanufacturing range from the more specific—e.g., synthesis of designed molecules and nanostructures, surface functionalization, or survival under extreme and non-clean-room manufacturing conditions—to the more general—e.g., how we create design tools for nanomanufacturing, and how we do hierarchical nanomanufacturing. Key R&D questions include the following:

- How do we specify each individual nanoelement, and how do we do this over large areas and volumes? Is the best approach growth-in-place or assembly?
- Can we provide external forces or an “environment” that directs the self-assembly and defines the functional development in a continuous, high-throughput manufacturing environment?
- How can we reduce defects and contaminants and increase yield when positioning and assembling?
- Do nanoscale properties remain once the nanostructures are integrated up to the microscale?
- How do we measure, characterize, and position “in-line,” during manufacturing?
- How do we ensure safe environmental and health working conditions, as well as safe products?
- How do we educate the next generation manufacturing workforce?

This report addresses these questions and highlights R&D topics that target particular needs and that have potential for accelerating progress in nanomanufacturing. The topics discussed—for which short-term, mid-term, and long-term opportunities have been identified—are as follows:

- Material development
- Material manipulation and control for manufacturing nanosystems
- Material patterning and interconnectivity
- Scale-up and integration with micro- and macro-systems
- Tools for manufacturing
- Tools for measurement and standards
- Modeling, simulation, analysis, and design
- Environmental and occupational health and safety issues
- Education and societal implications

KEY RECOMMENDATIONS

The following represent the major areas recommended for prioritization in order to expedite progress in nanomanufacturing:

- *Research for hierarchical nanomanufacturing.* Hierarchical integration will be used across dimensional scales, from atoms to molecules to the human length scale, to incorporate nanostructures into microscale architectures and macroscale products. Bottom-up, directed molecular or particulate assembly techniques will need to be combined with top-down, high-resolution, and high-speed macroscopic fabrication techniques. Various hierarchical systems architectures will create various technology platforms for nanomanufacturing.
- *Infrastructure development.* There is a need for geographically distributed nanomanufacturing research centers and user facilities with a variety of manufacturing tools to allow work on systems. These centers and shared facilities should network with existing nanoscience centers (e.g., those funded by the National Science Foundation, the Department of Energy, the National Institute of Standards and Technology, and the Department of Defense), serve as a resource for technology transfer for small and large business, and facilitate education and workforce training.
- *Modeling, simulation, and design.* Current molecular dynamics models are limited in time and space, such that prediction of realistic manufacturing processes is not feasible. New multiscale models need to be developed that can predict both yield and performance. Design tools using these multiscale models, equivalent to computer assisted design (CAD) or finite element analysis (FEA), are needed to enable rapid product development.
- *Tool development.* New metrology tools and manufacturing tools are needed to measure and manipulate nanostructures and nanocomponents, with an emphasis on in-line, real-time manufacturing rate capabilities to ensure high yield and precision.
- *Environmental and occupational health and safety.* In order to realize the benefits of nanomanufacturing, it is necessary to better understand the ramifications for workers, users, and the environment of health, safety, and environmental issues related to nanomaterials, nanomanufacturing processes, and nanotechnology-based products. Any potential issues or problems should be addressed proactively.
- *Education and societal impact.* The new nanotechnology-based processes will likely continue the manufacturing trend of decreasing physical and increasing information-processing requirements. An appropriately educated workforce, both for making the next-generation discoveries and for operating the nanomanufacturing processes, is vital to the continued economic success of the country. In addition, educating the general public about nanotechnology and nanomanufacturing is critical to achieving acceptance and realization of the promise of nanotechnology.

The contents of this report represent a snapshot in a rapidly evolving environment with respect to the state of nanomanufacturing knowledge. However, the goals and recommendations represent fundamental, comprehensive, multifaceted steps needed to accomplish the vision set forth—that of enabling the creation of highly efficient, high-rate, high-yield manufacturing processes that minimize materials and energy requirements, waste, and environmental impact while generating new products in electronics, energy, medicine, security, transportation, etc., that will benefit society.

1. VISION

Employing the novel properties and processes that are associated with the nanoscale—in the biological, chemical, electronic, environmental, materials, and other domains—promises huge benefits to society and our everyday lives. Highly efficient manufacturing processes are envisioned that minimize the use of materials and energy as well as environmental impact and waste, and that enable high-rate, cost-effective, repeatable production systems suitable for industrial implementation. Manufacturing of nanoscale structures, devices, and systems will be performed with a high degree of process control in sensing, assembling, and positioning matter at the nanoscale in order to achieve prescribed levels of performance in production and service. Hierarchical integration will be used across dimensional scales, from atoms to molecules to the human length scale, to incorporate nanostructures into microscale architectures and macroscale products. Bottom-up, directed molecular or particulate assembly techniques will be combined with top-down, high-resolution, and high-speed macroscopic fabrication techniques. New design methodologies will enable designers to quickly leverage these processes into mainstream industries. This range of developments will make possible the fabrication of new products and the offering of new services, thus enabling beneficial impacts of nanotechnology to the economy and society.

BACKGROUND

Based on advances in the understanding and control of matter at the nanoscale, new paradigms are expected in manufacturing and in the use of materials, devices, and systems, with applications in industry, healthcare, the environment, and national security. Nanoscale manufacturing has been practiced mostly as a top-down, down-sizing approach that has been critical to continued advancements in nanoelectronics. Practiced as a bottom-up approach, it is increasingly playing a significant role in the chemical, advanced materials, and pharmaceutical industries.

Manufacturing at the nanoscale will require new approaches besides down-sizing, or miniaturization, to achieve certain functionalities. As an example, gears have been studied and used for millennia as a macroscale mechanism to transmit motion and power (Fig. 1.1). However, carrying the design of gear transmissions to the nanoscale is challenged not only by the dominating effects of their high surface/volume ratio and the problems of friction, stiction, surface tension, electrostatic forces, etc., during operation, but also by major hurdles in gear manufacturing at the nanoscale in achieving a repeatable, economical, and high rate for industrial production. Nature offers effective molecular gear-like mechanisms, such as the F1-ATPase biomotor, for control of rotational motion [1]. Such biomimetic paradigms open up exciting research and industrial opportunities not only in the analysis of biological archetypes for generation of physical movements, but also in the design of bio-inspired devices and their large-scale manufacturing to achieve efficient and robust force and momentum transmission at the nanoscale.

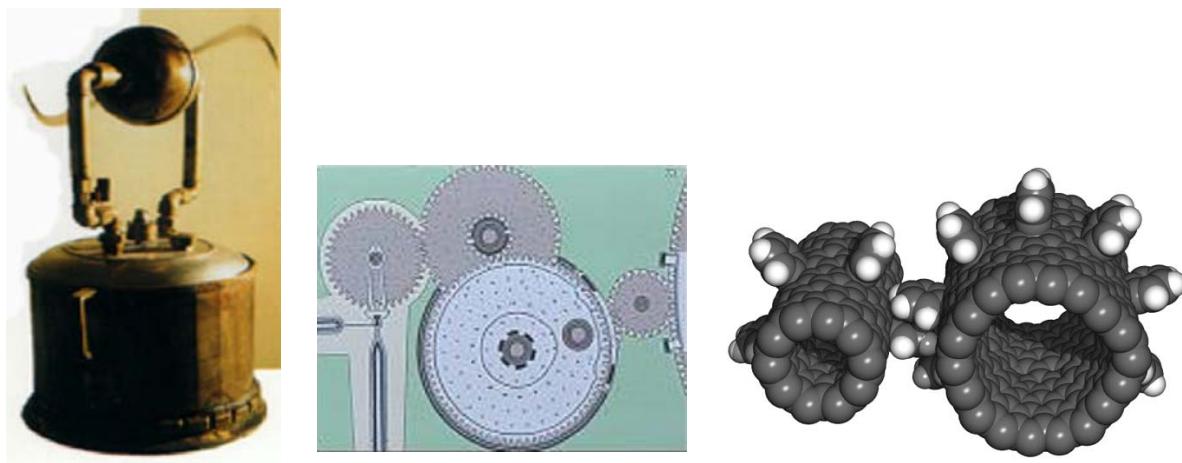


Figure 1.1. (Left) reconstruction of Heron's Aeolopile (ca. 80 AD); (middle) microscale gear (courtesy of Sandia National Labs) [2]; (right) nanoscale gear (courtesy of NASA/Ames).

Principles of mechanical, thermal, and fluid sciences have been developing for thousands of years. Heron of Alexandria (1st century AD) describes in his *Pneumatica* a working prototype of the *aeolopile*, the precursor of both the steam engine and the jet turbine (Fig. 1.1). Yet the development of transforming machinery for the industrial revolution had to be postponed for almost eighteen centuries because of the progress needed in engineering aspects (combustion, insulation, lubrication, bearings) and particularly in manufacturing research and infrastructure (mass-production casting, forging, machine shop equipment). Today, we are on the verge of a new technological revolution, founded on our ability to systematically control the arrangement of atoms and molecules at the nanoscale. The progression from the vision advanced by Feynman (1959) [3] to the development of the first tool—the scanning tunneling microscope (STM) used to measure the extent of an atom on a surface in 1981 [4], and later to manipulate and position individual atoms in 1990 [5]—to industrial-level manufacturing is ongoing. However, a rapid transition requires a synergistic research approach, utilizing the available resources in the most effective way. The vision developed by the NNI—using molecular interactions and specific phenomena and processes at the nanoscale to develop highly efficient manufacturing methods [6]—is quickly advancing to reality. A first generation of nanotechnology products, such as nanostructured dispersions, coatings, and materials, is already here. Similarly, scanned-probe techniques have enabled the fabrication of structures at molecular dimensions with increasing precision. High-rate and high-yield nanomanufacturing will be the key to achieving economically viable commercial products. Nanoscale manufacturing technologies include top-down manufacturing at sub-100 nm scale and bottom-up self-assembly methods. Theory, modeling, and simulation software are being developed to investigate nanoscale material properties and synthesis of macromolecular systems with desired functionalities such as biological sensing.

AREAS OF RELEVANCE

Manufacturing techniques at the nanoscale will have equal relevance as enabling components of traditional industries and as engines for revolutionary new products and services. Advances in manufacturing at the nanoscale are expected to accelerate commercialization of products such as nanostructured materials with novel and improved properties; information technology nanodevices (including advanced semiconductors, molecular electronics, and spintronics); nanobiotechnology and pharmaceuticals (e.g., diagnostics, implants, new drugs, and their therapeutic delivery);

1. Vision

measuring devices and tools for manufacturing; higher-performance safety and security technology (including sensors, adsorbents/filters/decontaminants); and nanoelectromechanical systems (NEMS). A sampling of existing or near-stage commercial products is given in Appendix B.

A one-day NNI meeting held in May 2002 at NSF (agenda in Appendix A) provided the foundation for the preparation of this report. Other related workshops held from 2002 to 2004 (listed in Appendix D) also addressed the role of nanomanufacturing in realizing various applications of nanotechnology.

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2. CRITICAL BARRIERS AND OPPORTUNITIES

AREAS OF OPPORTUNITY FOR NANOMANUFACTURING

The following sections briefly highlight areas of opportunity for nanomanufacturing, and the associated challenges and barriers that need to be overcome to realize those opportunities.

High Volume, Controlled Manufacturing of Monodisperse Nanoelements

Nanoscale building-block raw materials have been made available recently at quantities and qualities suitable for laboratory research but usually not for industrial manufacturing. These include quantum dots on surfaces, buckyball fullerenes, carbon nanotubes, nanoparticles, nanowires, nanofibers, and nanopores. The challenge for manufacturing is producing nanoelements in commercial-scale quantities with sufficient control of size, length, diameter, chirality, conductivity, etc., such that subsequent processing conditions and product characteristics can be well defined. For example, in the case of carbon nanotubes (CNTs), the yield of an assembly process utilizing CNTs as conducting nanowires would be highly dependent on the number of conducting vs. semiconducting CNTs in the sample, on their suitable length and diameter, and on their placement. Attempts to control diameter and structure (i.e., conductor, semiconductor) through the use of controlled seed sizes and “template” tubes (Fig. 2.1) have shown promising results [1], but process scalability is still a problem, as is rapid sorting for removal of defective nanotubes. Figure 2.2 shows that even in the somewhat less stringent production of nanofibers through electrospinning, the manufacture of continuous, individual nanofibers (versus random mats or fiber bundles) is still not controllable, due to instability in the nanofiber formation process.

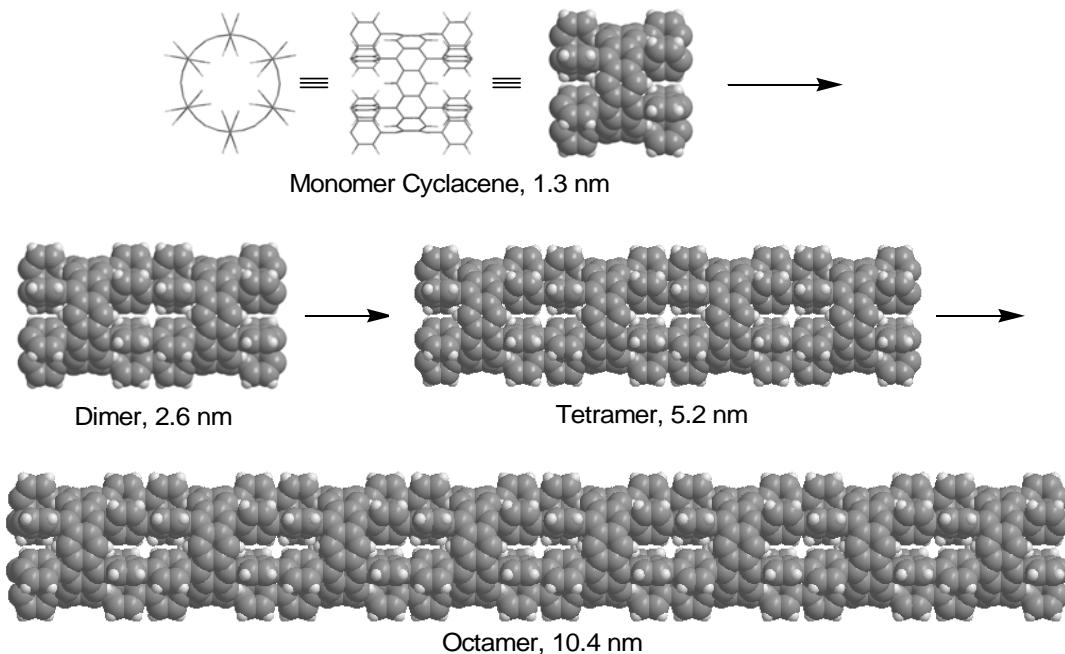


Figure 2.1. New technique for synthesizing uniform carbon nanotubes with controlled diameter and chirality (courtesy of G. Miller, University of New Hampshire; © 2006 American Institute of Physics; reprinted by permission from [1]).



Figure 2.2. A human hair in a nanofiber background. Random mats for filtration and scaffolds are commercially available, but more ordered nanofiber structures are not yet manufacturable (courtesy of eSpin Technologies).

Very Large Networks of Individually Addressable Processing Tools to Fabricate Heterogeneous Nanosystems

Heterogeneous nanosystems include multidimensional nanostructures made of dissimilar materials or components such as multilayered ferromagnetic/dilute paramagnetic semiconductor structures in spintronics, semiconductor and/or other inorganic structures such as in systems-on-chips, semiconductor/organic monolayer structures in molecular electronics, templated biomolecule scaffolds on semiconductor substrates, nanoparticulate dispersions or oriented nanotube/nanofiber reinforcements in nanocomposites, and biomolecular assembly on electronic circuits to detect specific biological events. Molecular beam epitaxy (MBE) and metal organic chemical vapor deposition (MOCVD) manufacturing tools have led to the commercialization of layered semiconductor nanomaterials for electro-optics, metallic nanolayers for giant magnetoresistance (GMR) devices, etc. However, no equivalent to MBE or MOCVD exists for manufacturing three-dimensional nanomaterials by design. The development of such manufacturing tools would allow precise control and high-yield manufacturing production.

Printed organic optoelectronic systems can be constructed in additive deposition of a variety of materials that are dissolved in aqueous and/or organic solvents, rather than by the methods already developed for silicon microelectronics [2].

Molecular gates (Fig. 2.3) can serve as the valves in a large microfluidic network (Fig. 2.4), with applications as a comparator array, a microfluidic memory storage device, or a DNA amplification chip. Challenges include understanding reaction kinetics and transport phenomena in confined spaces; surface chemistry at the wall of the molecular gates and the interface between the tool and the workpiece or substrate; functional characterization of the behavior of single molecular gates (e.g., to obtain characteristic curves for voltage vs. flow rate and operating characteristics such as maximum switching rates); and characterization of arrayed molecular gates for issues such as cross-talk, diffusion, and leakage.

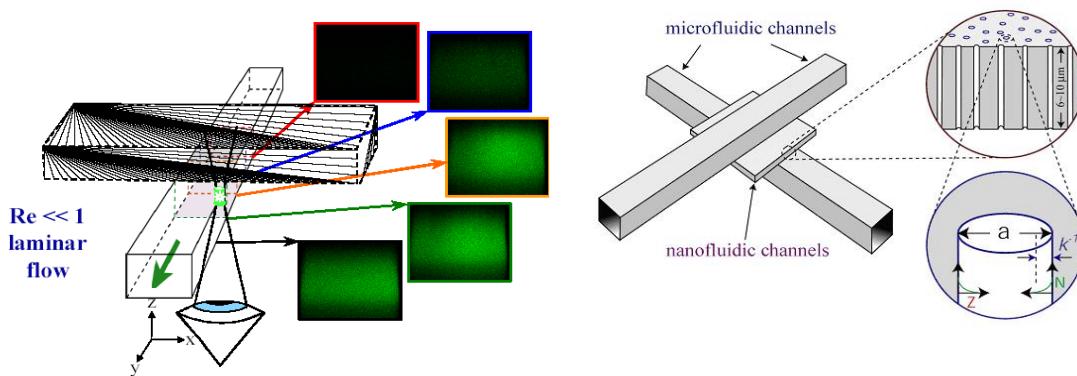


Figure 2.3. Rapid volumetric mixing occurs in the microscale channels due to the presence of nanocapillary arrays. The injection of fluorescein in phosphate buffer from the top source channel into the bottom receiving channel containing only the buffer exhibits this rapid mixing shown in these sequential confocal images (courtesy of M. Shannon, University of Illinois at Urbana-Champaign; right figure © 2003 American Chemical Society; reprinted by permission from [3]).

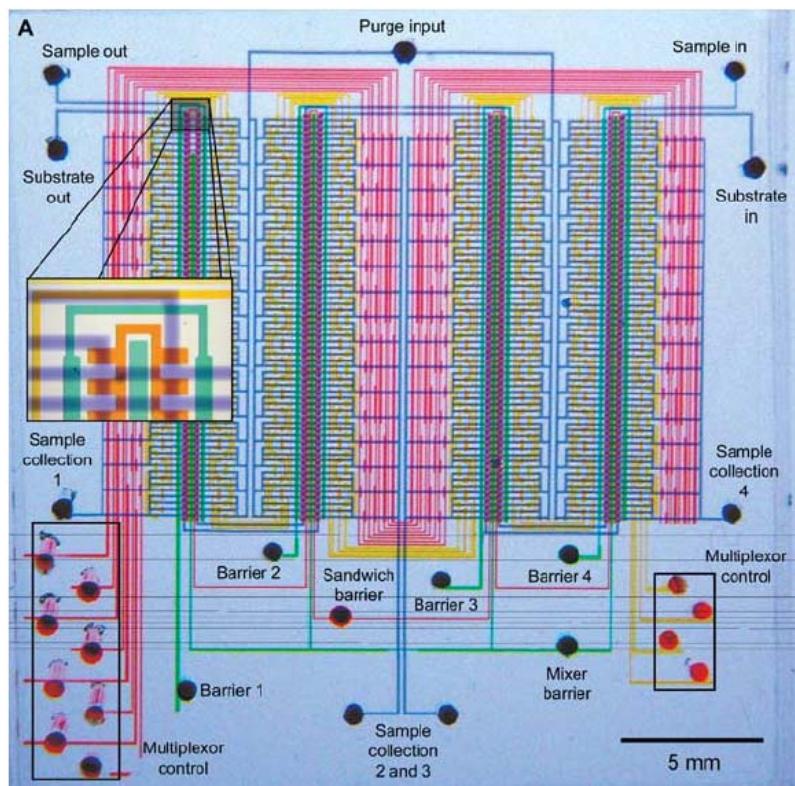


Figure 2.4. Optical micrograph of a very large-scale microfluidic network with 256 sub-nanoliter individually addressable reaction chambers. The various inputs—both reagent inlets and pneumatic control lines—have been filled with food dyes to visualize the channels and other elements of the network (© 2002 AAAS; reprinted by permission from [4]).

Manufacture of New Hybrid Structures to Obtain More Active, More Selective, Longer-Life Catalysts for Energy Applications

Industry has invested in R&D to develop shape-selective, highly reactive catalysts for more efficient refining of petrochemicals [5] (Fig. 2.5). The key to these new catalysts is being able to more closely tailor both the molecular size control (e.g., through controlled pore sizes ranging from 1.5 nm to greater than 10 nm) and reactivity (e.g., through controlling chemical composition and the positioning of metals and catalysts). Future applications envisioned for nanostructured catalysts include advanced chemicals manufacturing and biofuels production (e.g., from cellulosic feedstocks).

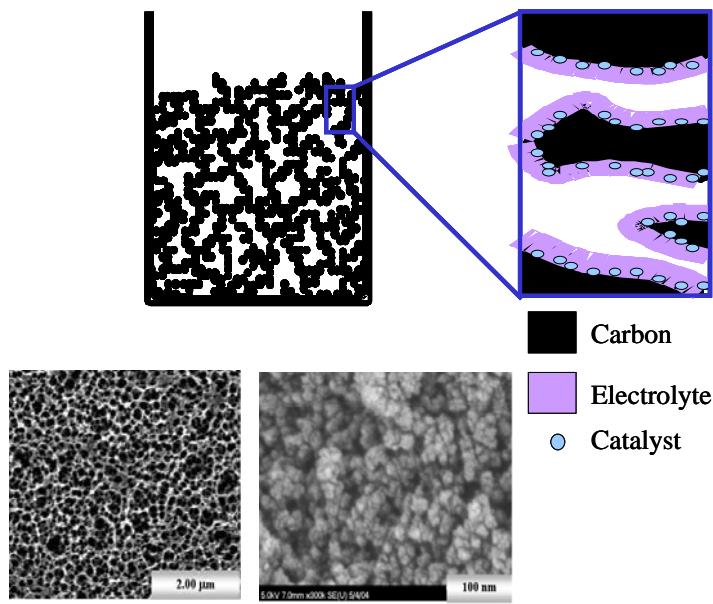


Figure 2.5. More efficient fuel cells can be manufactured through the synthesis of carbon aerogels with grafted fluoropolymer electrolytes and dispersed nanoparticulate Pt catalysts in the pores for PEM fuel cell catalyst supports. Schematic diagrams are shown (top) as well as images of the actual structures (bottom) (courtesy of S. Creager, Clemson University).

Patterning, Templating, and Surface Functionalization for Directed Assembly

Geometrical shaping and structuring processes at the nanoscale are at the heart of manufacturing technologies for production of functional devices and integrated multielement systems. Several two-dimensional (2D), parallel mask-based hard lithography methods are used, e.g., extreme ultraviolet (UV), X-ray (LIGA[†]), and e-beam. These are combined with serial scanning beam-based methods, e.g., electron and focused ion beam, two-photon lithography, or probe-based techniques including atomic force microscopy (AFM), scanning tunneling microscopy (STM), near-field optical and mechanical tip scribing, as well as parallel soft lithography based on molding (Fig. 2.6), contact nanoimprinting (Fig. 2.7), embossing, etc. These are also extended to 3D patterning by processes such as stereolithographic layering, as well as electrostatic, magnetic, and fluidic approaches (Fig. 2.8); directional growth; “pick and place” assemblies (Fig. 2.9); direct-write techniques (Fig. 2.10); diblock copolymer patterning methods (Fig. 2.11); and extrusion processes. Assistive material transfer technologies include plasma/laser vaporization, electrophoretic and laser-guided transport, as well as thermal spraying, cladding, and sintering. This wide variety of

[†] “Lithographie, Galvanoformung und Abformung”—German acronym for lithography, electroplating, and molding—micromachining technology using X-ray lithography invented in Germany in the early 1980s.

2. Critical Barriers and Opportunities

approaches also leads to many different barriers, but consistent throughout is the need for repeatable, scalable, and controllable processes.



Figure 2.6. High-rate processes such as injection molding can be adapted to manufacture parts with nanoscale features at seconds per part. The questions include how the polymer will flow in nanoscale channels and pits (courtesy of C. Barry and J. Mead, University of Massachusetts, Lowell).

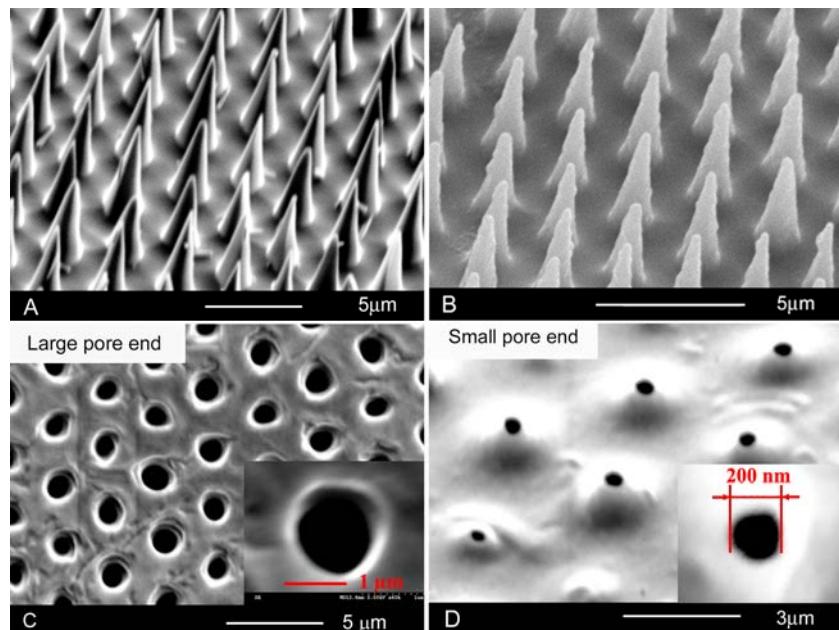


Figure 2.7. Scanning electron microscope (SEM) images of: (A) nanotip array; (B) PVA (polyvinyl alcohol) sacrificial template; (C, D) polymer membrane with highly ordered anisotropic pores. A sacrificial template imprinting method was created to produce polymer membranes with highly ordered uniform pores. Polymer self-folding, in response to interfacial energy conditions, can be used to create 3D enclosed shapes (e.g., for drug delivery) from these 2D membranes (courtesy of L. J. Lee, Ohio State University).

2. Critical Barriers and Opportunities

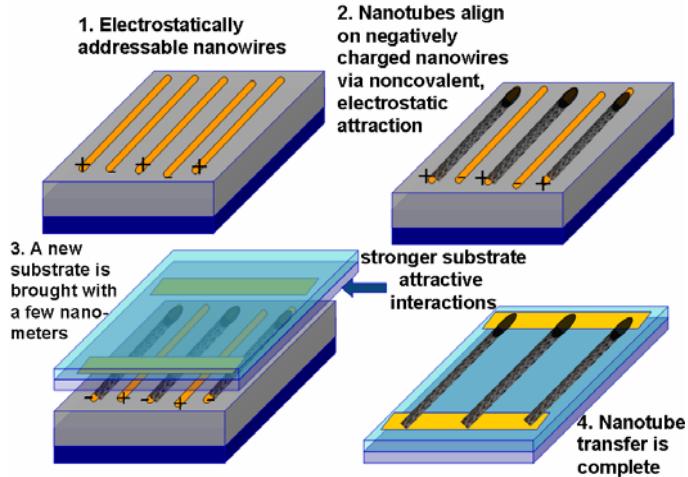


Figure 2.8. A potentially more rapid and flexible approach to positioning and aligning CNTs requires better understanding of templating and adhesion/removal (courtesy of A. Busnaina, Northeastern University; J. Mead, University of Massachusetts, Lowell; and G. Miller, University of New Hampshire).

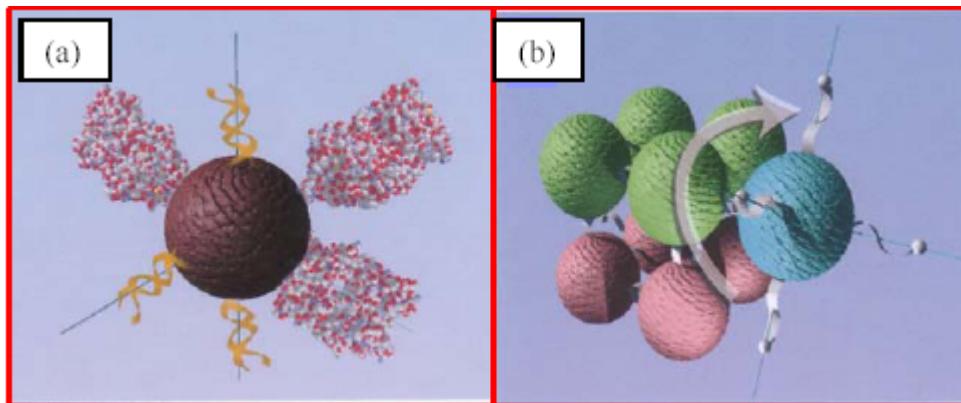


Figure 2.9. Another example is the development of a microelectronic array-based “pick & place” assembly platform containing electronically-addressable microlocations and nanolocations to which various molecules, macromolecules (DNA, proteins, etc.), and nanostructures (quantum dots, photonic crystals, carbon nanotubes, etc.) may be selectively positioned and oriented. This electronically addressable pick & place platform can be used to develop techniques that allow the selective and high-precision functionalization of nanocomponents. The ability to carry out such high-volume precision functionalization of nanocomponents is a prerequisite to the subsequent ability to self-assemble these components into more heterogeneous higher-order 2D and 3D structures (courtesy of X. Zhang, the Nanoscale Science and Engineering Center [NSEC] for Scalable and Integrated Nano Manufacturing [SINAM], University of California, Los Angeles; and M. Heller, University of California, San Diego) [6].

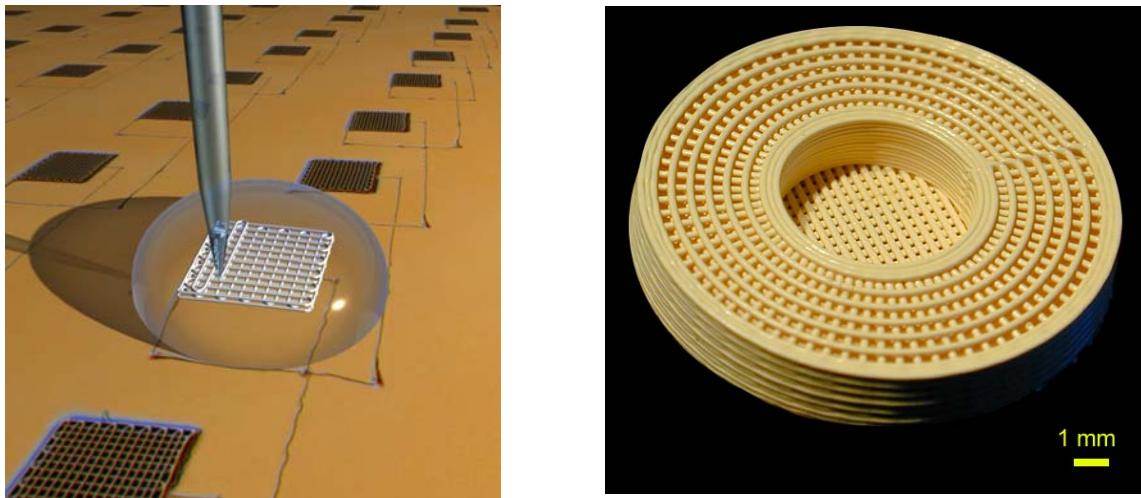


Figure 2.10. Other examples of direct write methods include use of colloidal inks containing nanoparticles. Fundamental questions involve designing the nanoparticle ink to obtain the proper viscosity, solidification, and consolidation characteristics (courtesy of J. Lewis, University of Illinois at Urbana-Champaign; left figure © 2004 Elsevier; reprinted by permission from [7]).

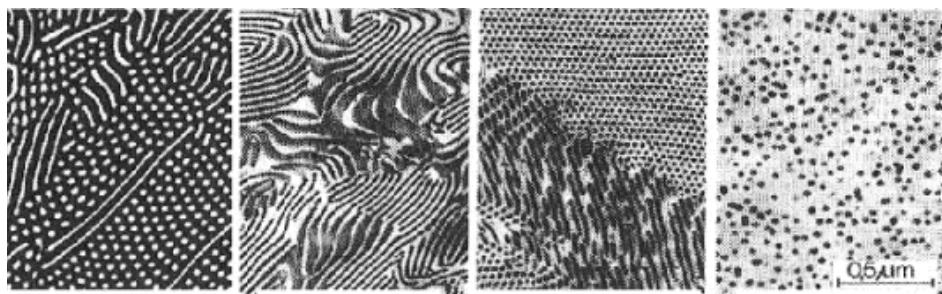


Figure 2.11. Diblock copolymers can be used to obtain long-range order, but issues of stability and survivability—under high-rate processing conditions—of templates based on these materials and chemical functionalization remain a critical problem (courtesy of the Mauritz Research Group) [8].

Interconnects: Interfacing with the Micro- and Macro-Worlds

Research on multichip modules and microelectromechanical systems (MEMS) has shown that a major challenge for achieving nanometer-scale products will be the ability to communicate and interface with the macroscale world. Thus, a fully scalable nanomanufacturing platform is required to facilitate the multiscale integration from nanoscale to microscale, and further to the macroscale (Fig. 2.12). Nanoscale interconnects are required that are fast, reliable, cost-effective, consume little power, and that have the ability to link structures of diverse types, materials, and sizes. The metrology necessary to ensure that the nanodevices are “known-good” prior to and after connection is another challenging issue. The “known-good die” problem is a major challenge for multichip module providers.

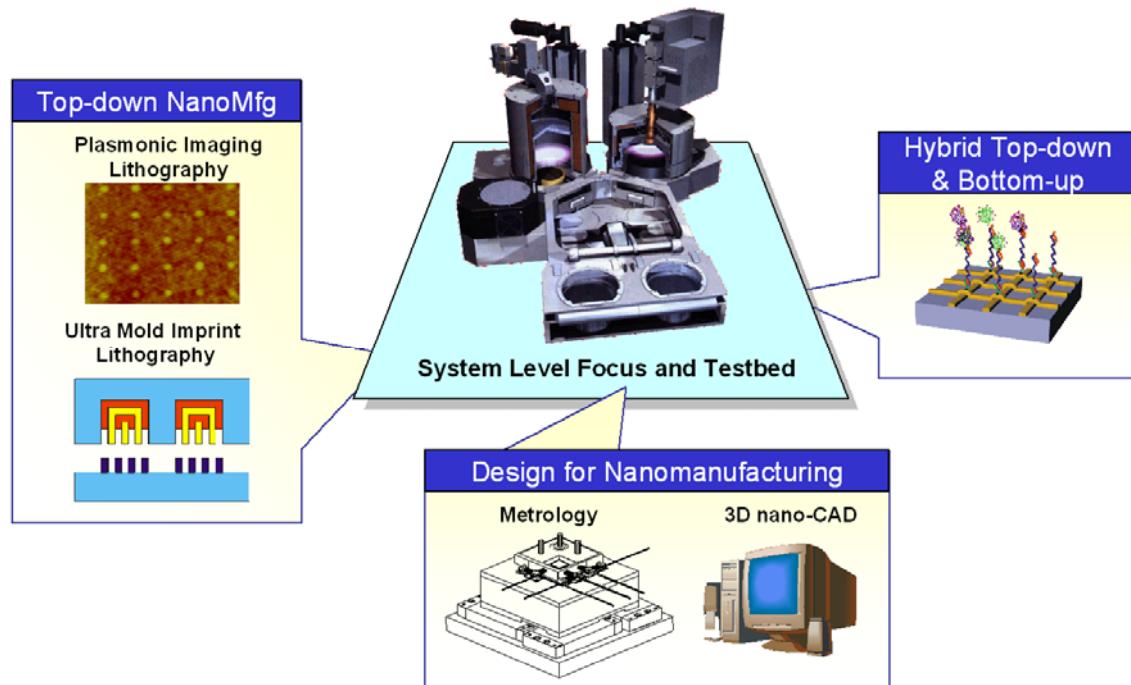


Figure 2.12. Nanocluster tools with multiple processes conducted on the same substrate (courtesy of X. Zhang, SINAM NSEC, University of California, Los Angeles) [6].

Positioning and Registration for Multilayer, Multiprocess Manufacturing

To manufacture at the nanoscale, equipment must be developed with nanometer precision for positioning. An additional hurdle is the need for multiple step registration. One approach to addressing the need for registration of layers or components is the use of nanocluster tools with multiple processes conducted on the same substrate without the need for transporting the substrate from one machine to another, as illustrated in Figure 2.12. This, however, does limit the manufacturing to more batch-type processing. Continuous reel-to-reel processing will require new methods of registration, including possibly self-registration, that can handle the rapid motion of the substrate [6].

Biologically Inspired Assembly/Molecular Manufacturing

One of the farthest-reaching challenges of manufacturing at the nanoscale is to achieve the great breadth demonstrated by nature in using self-assembly and extend this to a wide range of hierarchical structures. Some form of directed self-assembly is necessary to achieve true molecular manufacturing—i.e., control over fabrication of a heterogeneous molecular structure under commercial scales and rates of production. Critical issues include precision synthesis or the ability to obtain the same sequence, composition, block and chain lengths, etc. Self-assembly is generally capable of generating very uniform structures. The problem arises when greater diversity of structure and composition is desired and the kinetics and dynamics must be fast enough, yet controllable, for a commercially viable process time. By understanding self-assembly processes or mechanisms better, there is a potential to fabricate supramolecular structures using similar interaction potentials (e.g., shape, electrostatics, hydrophobicity, metal coordination, and controlled arrangement of functional sites) [9]. Some promising routes involve the modification of viruses and

proteins to serve as assemblers of newly designed materials, but issues such as achievable heterogeneity and yield in a batch bioprocess remain to be tackled. Figure 2.13 illustrates one approach being taken along these lines [10].

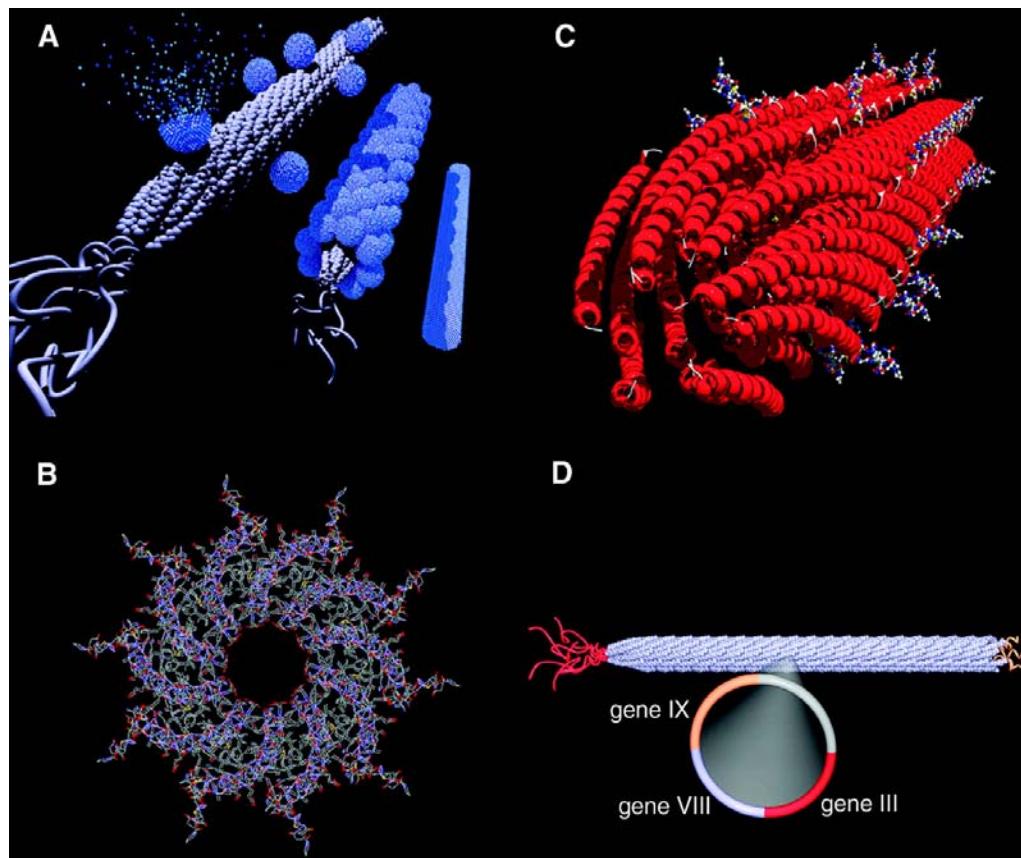


Figure 2.13. Visualization of the M13 bacteriophage and the subsequent nanowire synthesis. The gP8 coat assembly was reconstructed from the X-ray fiber crystallographic data. The gP3 and gP9 proteins located at the proximal and remote ends of the virus are not to scale and serve as representations of the proteins. (A) The nanowire synthesis scheme is visualized for the nucleation, ordering, and annealing of virus-particle assemblies. (B) The symmetry of the virus allows for ordering of the nucleated particles along the x, y, and z directions, fulfilling the requirements for aggregation-based annealing. (C) The highly ordered nature of the self-assembled M13 bacteriophage promotes the preferred orientation seen in nucleated particles through the rigidity and packing of the expressed peptides, which is visualized at 20% incorporation. (D) The construct of the M13 bacteriophage virus showing the genetically modifiable capsid and ends, specifically the gP3, gP8, and gP9, which are coded for in the phagemid DNA enclosed within the virus capsid (courtesy of Angela Belcher, MIT, © 2004 AAAS; caption and figure reprinted by permission from [10]).

DESIGN NEEDS

Expansion of nanotechnology beyond a few niche products requires the establishment of predictability—i.e., the ability to model, simulate, and design the desired process and product parameters. Predictability presents an extreme challenge as complexity increases and as products and processes cross size scales and functional domains. A robust feedback loop between measurement of nanomaterials properties and process control is a critical requirement in effective design.

Begin the Transition

The transition from fundamental analysis and understanding of nanoscale phenomena (nanoscience) and synthesis or fabrication of nanostructures with engineered functions in the laboratory (nanotechnology) to high-rate, high-quality production of integrated systems in industry (nanomanufacturing) is presently an emerging field. Recent advances can be attributed to progress in building the necessary raw materials and building blocks, in integrating processes of dissimilar elements, in shaping the geometry of multidimensional structures, in connecting the process conditions to the resulting product features, and in hardware instrumentation and simulation software for construction and characterization at the nanoscale.

Advanced Instrumentation and Simulation for Analysis

Analytical equipment hardware for laboratory experimentation, besides off-line scanning probe and spectroscopic microscopy instruments for characterization of nanomanufactured structures, must be extended to in-process metrology techniques, including near-field interferometry and nanopattern encoding, and real-time imaging methods such as concurrent focused ion beam (FIB) process/SEM imaging, etc. In addition, computational software such as multiscale molecular dynamics simulations, typically applied for structure-property in-service analysis, is becoming available for process-structure studies during manufacturing processing.

Manufacturing Processes and Equipment Models

The distinction between manufacturing process performance and product performance is blurred and likely interwoven when considering nanoscale products. Following the path of today's precision machining industry, nanometer-scale manufacturing equipment manufacturers must demonstrate to their customers the performance capabilities of their equipment with assigned uncertainties. This will require rigorous performance measures that are traceable to fundamental standards such as length and force.

Design of Manufacturing Processes/Manufacturing "By Design"

The interdependence between product design and manufacturing process and the requisite holistic approach adopted at larger fabrication scales is even more clearly realized in nanomanufacturing because of the peculiarity of the matter-process interaction mechanisms at the nanoscale. The geometrical and material designs of nanodevices are adapted to the structuring capabilities of the new nanomanufacturing technologies; inversely, sequences of multiple diversified process step protocols are developed for implementation of custom-designed structures.

The classic design paradigm based on hierarchical composition of well-characterized compatible components, identifiable well-behaved interfaces, and reduced complexity via abstraction will have to be extended to encompass the realities of nanofabrication. This will require an extension beyond current "design for manufacturing" methodologies to "design of manufacturing" where the design of the final artifact is performed concurrently with the specification of the design process to create the artifact. Statistical models of yield, performance, and failure will become central to the abstractions developed and used by designers to create reliable systems from multiple base technologies, assembled using top-down and bottom-up techniques, and produced in mass quantities.

AREAS OF RELEVANCE BY INDUSTRY SECTOR

- *Advanced materials industries.* This pertains to materials with improved physical, chemical, and biological properties. Examples are to be found in materials, tools, chemical, construction, textile, and other industries. Such materials will include catalysts, nanostructured polymers, and nonwoven fabrics from electrospun nanofibers; strong and lightweight nanoparticles, nanotube- or nanofiber-reinforced polymer composites and metal alloys; nanoporous polymer and metal foams; nanograined superhard coatings for machine tools, molds, dies, and instruments; superplastically deformable nanopowder-consolidated metals and ceramics for shape-forming; and smart materials with embedded conductive, piezoelectric, magnetostrictive, shape memory alloy, or magnetorheological elements for color, texture, conductivity control, and sensory or active behavior. Furthermore, nanoscale manufacturing will advance the development of novel materials by enabling the construction of artificial materials from individual atoms and molecules to achieve the desired functionalities.
- *Electronics, information technologies, and communications industries.* Examples include low-power, high-density electronic memories; power-adaptive computational circuits; molecular or nanostructured switches, amplifiers, and interconnects for analog/digital data processor and storage devices (including single-electron, ferroelectric, spin-, and magneto-electronics); on-chip optical interconnects; molecular electronics and hybrid technologies; DNA computation platforms; liquid crystal and photonic flat/flexible panel displays; audio and haptic devices and sensors; photonic crystals for optical signal processing in optical fiber communications and amplified multifrequency transmission in optical networks; nanostructured wireless transmitter/receiver microdevices for local tag identification (radio frequency) or satellite localization (Global Positioning System); and low-power mobile communication devices.
- *Power and energy industries.* Examples include nanostructured catalysts (on zeolites, aerogels, hydrogels, etc.) for reactors; consolidated nanoparticle or nanostructured proton exchange membranes for fuel cells; nanostructured cells for flexible photovoltaics; artificial photosynthesis; new types of batteries; and high-pressure containment tanks.
- *Pharmaceutical, biochemical, and food industries.* Examples include chemical/drug screening arrays, synthesis and processing of new drugs, nanoparticle dispersions and aerosols, and quantum dot fluorescent tags for biomolecule identification.
- *Medical, health, environmental, and safety industries.* Examples include drug/gene bioassay arrays for genomics and proteomics research and clinical therapy; nanoparticle and nanosphere medication/gene vectors; nanostructured biomaterials (hydroxyapatite, calcium phosphates) for implants and prosthetics; implantable assistive microdevices such as programmable medication dispensers, pacemakers, pressure/glucose detectors, etc; sterile surface catheters and surgical tools; design and synthesis of supramolecular organic and inorganic molecules, with special emphasis on biological entities such as DNA and proteins for disease control; nanoparticle agent and sensor technologies for medical imaging and diagnostics; nanostructured biocompatible/biodegradable scaffolds for artificial tissue engineering and regenerative medicine; microbe, viral, and toxic gas sensors for warfare defense and emission control; and filtration membranes for desalination and pollution control. Manufacturing for any medical applications, including even making large enough batches of material for trials, must adhere to the requirements of Good Manufacturing Practices (GMP) certification.
- *Aerospace, automotive, and appliance industries.* Examples include high strength/weight ratio nanostructured alloy and composite materials for fuselages, bodies, and other structural elements; highly resistive or ultralow-friction layers for thermal barrier coatings, bearing surfaces, etc., in jet, internal combustion, and hydraulic/pneumatic engines and elements; and

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nanostructured MEMS and NEMS devices such as accelerometer and gyroscopic sensors, fuel injection and supplementary restraint fluidic actuators, or reconfigurable control surfaces.

- *Service industries.* This includes the users of nanomanufactured products. These industries span nanostructured and nanofabricated product design and prototyping companies; market analysis and marketing of such products; research and development laboratories and consulting firms; intellectual property development and management services for nanomanufacturing technologies; related education at the technical school or college/university level; workforce training of professionals for nanomanufacturing industries; and software development for product design, process simulation, modeling and control, and continuous learning.

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3. RESEARCH GOALS AND ANTICIPATED OUTCOMES: SHORT-, MEDIUM-, AND LONG-RANGE

CHALLENGE AREAS AND PRIORITIES

Nanotechnology will fundamentally change the way both basic types of manufacturing—continuous and discrete—are conducted in the future. Continuous manufacturing refers to the production of bulk substances or materials (e.g., chemicals or rolls of sheet metal). Discrete manufacturing is the production of individual parts (e.g., bolts or devices such as integrated circuits or assembled systems such as computers). Nanostructures, frequently controlled at the single atom/molecular level, are the “raw material” for manufacturing at the nanoscale. As a result, the processes and equipment for manufacturing at the nanoscale are expected to be significantly different from even those currently used for microfabrication in the size range over 100 nm. The special research opportunities include those listed in Table 3.1, covering the present to about twenty years from now.

Table 3.1
Nanomanufacturing R&D and Education Challenge Areas and Key Priorities/Goals
2005-2015, 2010-2015, 2010-2025

R&D Challenge Areas	Key Priorities/Goals
Material development	<ul style="list-style-type: none">Systematic methods for reproducible synthesis of nanostructures/nanoelements/nanoscale building blocks (e.g., quantum dots, tubes, wires, particles, fibers, films) from various materials, with control of structure, properties, and functionsSynthesis of adaptive nanostructures with programmable properties (e.g., threshold voltage, output conductance)Replication methods for nanostructuresStructures with low defects at the atomic scaleCharacterization and control of support materials (e.g., photo resist)
New material/device/system architectures	<ul style="list-style-type: none">Ability to turn on, turn off, or program specific blocks or individual elements in an organized assemblyDirected selective and nonselective growthInterfacial control during manufacturingThermodynamic and chemical stability
Directed (self-)assembly processes for heterogeneous integration of nanocomponents into 1D, 2D and 3D devices	<ul style="list-style-type: none">Use of various external fields for directed self-assembly and disassembly, positioning, orienting, dispersing, and/or clustering molecules, macromolecules, and nanoelements [1, 2]Programmed (directed), hierarchical self-assembly of building blocks into functional devices and systems (e.g., bio-inspired, biomimetic manufacturing [3])Control of defect formation (e.g., due to thermodynamics)
Scale-up methods; integration of nanostructures into larger-scale structures	<ul style="list-style-type: none">High-rate production of nanostructures (particles, layers, bulk, and various structures) and intermediary standard componentsPackaging and transportation of nanomaterials and nanoelements so as to present the materials into the process in a desired orientation, position, time, and sequenceIntegration of bottom-up and top-down fabrication techniques into the most cost-effective and optimal throughput manufacturing [4]Fabrication methods for use under non-clean-room conditions

3. Research Goals and Anticipated Outcomes

R&D Challenge Areas	Key Priorities/Goals
	<ul style="list-style-type: none"> Parallelization and integration of multiple manufacturing techniques (e.g., parallel probe or beam arrays, fab-on-a-chip approaches, IBM millipede, sequencing arrays) Rapid, reproducible, and durable pattern transfer techniques Interconnectivity of defined elements in architectures other than next-neighbor form for reliable signal transmission and for achieving high speed with controlled power; developing 3D interconnect architecture as governed by Rent's design rule when the density of the nanodevice increases; modular interconnects Multiscale patterning (nano, micro): multiscale packaging; multiscale platforms to interface nanoscale devices to micro- and macroscale instruments Design tools Systems approach to improve the throughput and yield of nanomanufacturing Integration with existing production equipment Fault-tolerant designs and quality control
Tools for manufacturing, measurement, and standards (nanoscale metrology)	<ul style="list-style-type: none"> Technologies for chemical and structural characterization and control of nanoparticles and other nanoelements Technologies for <i>in situ</i> and <i>ex situ</i> characterization and control of electrical, optical, and other properties of a variety of devices and systems Technologies for characterization and processing of nonconducting, compliant surfaces (e.g., organic, biological, and other soft components) Characterization of geometries and positions of nanoelements Characterization of defects, measurement of reproducibility, rapid comparison with standards Taxonomy and standardization of structural and functional properties of the nanoelements, and coding into information databases for use in design and process tools (key is improved interoperability and information-knowledge exchange) Developing a high-precision metrology platform for registration and translation (e.g., to 1 nm accuracy across 250 mm range) Tools and platforms to connect the nanoscale and micro- or macroscale Measurement of surface/interface properties Developing 3D processing and nondestructive subsurface monitoring and visualization technologies Developing integrated in-process sensing and monitoring Developing tools for localized assembly, repair, trimming, or decontamination Telefabrication and telecharacterization-capable equipment and instrumentation User-intuitive interfaces Accelerated testing of manufacturability and reliability
Model development	<ul style="list-style-type: none"> Multiphenomena and multiscale product and process design methods, integrated with measurement capabilities Energy and momentum transfer processes in nanoscale systems Coupled length and time scales Combinatorial processing approach Virtual environment for modeling and simulation Product realization; virtual product realization Predictability of lifetime of nanocomponents/subsystems under operating conditions Predictive models for both yield and performance Real-time control algorithms appropriate for closed-loop, <i>ex situ</i> or <i>in situ</i> control at the desired resolution and bandwidth requirements Models for analytical capability for real-time processing and characterization feedback

3. Research Goals and Anticipated Outcomes

R&D Challenge Areas	Key Priorities/Goals
Convergence with biosystems	<ul style="list-style-type: none"> • Biosystems for tissue engineering; biotic-abiotic interaction • Neural systems; spinal cord research • Biologic agents to the electronic circuits for biosensing applications
Environmental and occupational health and safety	<ul style="list-style-type: none"> • Specific safety criteria • Handling of manufacturing waste streams • Environmentally friendly • Life cycle analysis, including disposal of micro- and macroscale products containing nanoelements • Occupational safety and health practices in the production and use of nanomaterials • Occupational monitoring, engineering controls, personal protective equipment, occupational exposure limits, and administrative controls
Education for nanomanufacturing	<ul style="list-style-type: none"> • Workforce training • K-12 interest in science/math/engineering • Inter- and cross-disciplinary curricula

FOUR GENERATIONS OF PRODUCTS

The rudimentary capabilities of nanotechnology today for systematic control and manufacture at the nanoscale are envisioned to evolve in four overlapping generations of new nanotechnology products with different areas of R&D focus [5], as outlined below. Each generation of products is marked by creation of commercial prototypes using systematic control of the respective phenomena and manufacturing processing.

1. *First generation* of products (beginning around 2000): passive (steady function) nanostructures, illustrated by nanostructured coatings, dispersion of nanoparticles, nanocomposites, and bulk materials—nanostructured metals, polymers, ceramics.
2. *Second generation* of products (beginning around 2005): active (evolving function) nanostructures, illustrated by transistors, amplifiers, targeted drugs and chemicals, actuators, and adaptive structures.
3. *Third generation* of products (beginning around 2010): 3D nanosystems and systems of nanosystems using various synthesis and assembly techniques such as bio-assembly, nanoscale robotics, evolutionary systems, networking at the nanoscale, and multiscale architectures.
4. *Fourth generation* of products (beginning around 2015): heterogeneous molecular nanosystems, where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices, and fundamentally new functions will emerge from their engineered structures and architectures. Since the path from fundamental discovery to nanotechnology applications takes about 10–12 years, now is the time to begin exploratory research in heterogeneous molecular nanosystems.

Examples of Enablers for Successive Product Generations: Nanoelectronics Challenges[‡]

Scaling semiconductor devices to ever-smaller dimensions has enabled incredible improvements in the performance, energy usage, and cost of integrated circuits over the past four decades. These

[‡] Note that research challenges for nanoelectronics/manufacturing are detailed in the 2002 and later updates of the International Technology Roadmap for Semiconductors (see <http://www.itrs.net/reports.html>).

3. Research Goals and Anticipated Outcomes

advances have revolutionized electronics, information technology, and communications. However, if we are to continue this progress for more than roughly another decade, a pair of technical challenges must be overcome. The first challenge is to develop a new nanomanufacturing paradigm that allows continued reduction in cost-per-function (e.g., logic gate or bit of memory). Despite significant incremental advances, the traditional “masked-lithography of thin-films” approach (first generation of nanotechnology products) is becoming so complex that the cost trend is threatened. In particular, a future manufacturing technique that lowers the cost of capital equipment, pattern generation, and atomic-level process control will be required. The solution might be found in the broad area of research on directed self-assembly, possibly adapting biological techniques. Ideally, a suite of advanced nanomanufacturing methods would be developed that could build a wide variety of devices, including CMOS scaled to its ultimate limits.

The second challenge is to develop new devices/circuits that extend the industry’s historical rates of improvement for at least several more decades. CMOS is already being scaled into a regime where the tradeoff between performance and power consumption forces significant compromise. In the medium term (second generation), this issue may be addressed by one or more “post-CMOS” (but still charge-based) device technologies such as carbon-nanotube or single-electron transistors. At the device level, such structures have been studied in industrial labs for a number of years and are now fairly well understood. The practical problems for their implementation into complex integrated circuits are almost entirely at the manufacturing level and are thus examples of the first challenge outlined above. As charge-based devices, they tend to remain limited by most of the interconnect charge-transport issues (e.g., parasitic capacitance) and near-equilibrium thermodynamic constraints that afflict CMOS. Therefore, the long-term solutions required by the second challenge (third and fourth generation) might be found in devices based on state variables other than electric charge (e.g., electron-spin, nuclear-spin, or photonic states).

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4. SCIENTIFIC AND TECHNOLOGICAL INFRASTRUCTURE

THE CRITICAL ROLES OF INFRASTRUCTURE DEVELOPMENT

To implement the nanomanufacturing vision described in Chapter 1 of this report, there is a clear need to complement and extend existing predominantly scientific and prototyping facilities for nanoscale research within their respective engineering and manufacturing infrastructures. This will allow attainment of a powerful armory of resources to address synthesis and scale-up of nanoscale materials and structures into functional devices, integrated systems, and interconnected architectures, leading to useful products and services at physically relevant size scales. Much like in the human organism, where nanoscale structures of molecular organelles in the cell nuclei are functionally integrated into microscale assemblies at the cell level, and further into the variety of mesoscale tissues and eventually into the diversified macroscale organs of the body, it is expected that engineered nanostructures and functions will provide the building blocks for fabrication across dimensional scales. To provide the required multifunctionality, such technologies will naturally need to encompass and transcend the entire spectrum of energetic or disciplinary domains, including, for example, their mechanical, fluidic, electrical, magnetic, optical, chemical, or biological aspects. However, the fundamental manufacturing research issues of producibility, predictability, and productivity of such technologies must also be factored and implanted into this endeavor in order to harvest industrially viable and broadly useful outcomes from such an investment in nanomanufacturing infrastructure. The wide range and high complexity of nanoengineered systems and products requires a collaborative, multidisciplinary nanomanufacturing research approach.

There is a parallel need to maintain and upgrade the existing nanoscience and nanofabrication resources. Analysis and prototyping equipment such as nanoscale microscopy and measurement instruments are based on state-of-the-art technologies that are changing rapidly, and they must be regularly replaced. An integrated approach is necessary that provides the resources to acquire or develop the equipment and also supports the technical staff needed to operate it efficiently. If the relevance and utility of the skilled workforce is to be promoted in light of the increasingly interdisciplinary nature of nanomanufacturing, there is a need to diversify the scope of workforce development activities into interrelated directions such as the chemical, biological, and environmental domains.

Following a systems approach in nanomanufacturing, there is an identified need to systematize and link new nanomanufacturing infrastructure with existing resources into a comprehensive, coherent network. Similar to a recent paradigm of the National Earthquake Engineering Simulation network, an integrated nanomanufacturing infrastructure can capitalize on world-class cyber-networking and communication structures (such as Internet-2), to provide a hierarchical systems architecture with functionality and utilization larger than those of the sum of its components. This can consist of properly connected virtual centers and sub-networks, optimizing physical accessibility of the resources to all geographic areas of the country and promoting their broader use via teleoperation (telecharacterization, teledesign, and telefabrication of nanostructures) over the electronic network. For the purpose of maximizing their utility, it is important that the Federal investment in nanomanufacturing infrastructure be shared and co-funded as much as possible by state governments, academic institutions, and industrial organizations that will encourage their members to take advantage of the joint resources. See the National Center for Manufacturing Sciences report

4. Scientific and Technological Infrastructure

on its survey of nanomanufacturing in the United States [1], particularly the responses regarding government roles.

Beyond enabling and shaping new research directions in nanomanufacturing, this infrastructure can be the cradle of new educational and training programs in science and engineering, as well as of public information and participation activities that reach out to the broader society. Education of human resources in this nascent field of knowledge, including teaching and mentoring of future nanoscale science and engineering researchers and educators and training of a professional workforce for the emerging nanotechnology industry, is at least as important as the infrastructure facilities. These resources will provide the platform for establishing new educational programs in nanomanufacturing, from interdisciplinary college majors and disciplinary minors, to graduate degrees, post-doctoral programs, and continuing education certificates, to high-school summer courses and throughout the K-12 curriculum. Training courses and seminars for practicing professionals and industry personnel also will utilize these facilities, either by hands-on projects and demonstrations or by teleoperation via the Internet. The networked resources will attract involvement of researchers from other related fields, instructors of multiple related themes, as well as nontraditional contributors to nanotechnology such as behavioral, economic, and social scientists. At the same time, the infrastructure will be open to the public for laboratory visits and virtual demonstrations on the Web, and will sponsor special nanotechnology awareness events and activities to promote public understanding of the new technologies, their new opportunities for education and employment, and the technologies' impending impacts on society.

The nanomanufacturing infrastructure should include the following features and capabilities:

- *Geographically distributed nanomanufacturing research and nanofabrication user facilities*, including adequate characterization and process development capabilities, are needed for both vertical functionality research/development and education/training of the workforce.
- *Nanomanufacturing facilities that provide broad opportunity and involvement* for health, environmental, social, and economic scientists; underrepresented groups; and foreign visiting scholars for promotion of international precompetitive research and education collaborations.
- *Support for small business incubation and growth* to accelerate manufacturing technology transfer to industry. Effective strategies are needed for handling intellectual property issues and promoting technology transfer, as are *marketplace-neutral resources* to facilitate integration of people, software, and science-based understanding across the entire manufacturing enterprise.
- *Efficient networking of new nanomanufacturing facilities* to the existing nanoscience and nanotechnology center infrastructure (including university, national laboratory, and industry facilities), and capability for teleoperated remote manufacturing (telefabrication, telecharacterization) for wider accessibility. Appropriate incentives should be provided to promote sharing of facilities, staff time, and other resources.
- *Standardization and proper documentation of nanofabrication procedures and process conditions* to ensure efficiency in accessing the shared facilities and low cost of commercial products. *Libraries* of components, processes, and simulation models should be available to electrical, mechanical, chemical, and biological design engineers, along with *computer-aided design tools* accessible to practicing engineers and compatible with current manufacturing tools, as well as infrastructure for development of measurement and manufacturing tools and standards.
- *Support for development of applications* of nanotechnology relevant to agency missions and national priorities such as homeland security.

REFERENCE

1. National Center for Manufacturing Sciences, Inc. (NCMS), *2005 NCMS Survey of Nanotechnology in the U.S. Manufacturing Industry* (NCMS, Ann Arbor, MI, 2006; <http://www.ncms.org/publications/PR/2006/2006-7-12NanoReport.htm>).

5. R&D INVESTMENT AND IMPLEMENTATION STRATEGIES

Over the past few years, the Federal Government has spearheaded support of nanotechnology facilities through the National Nanotechnology Initiative, which united the Federal agencies in a coordinated and complementary development plan. Many individual states, such as California, Florida, Illinois, New York, Pennsylvania, and Texas, have also followed this example by generously committing resources to nanotechnology. In the international arena, the European Commission, through its Framework programs, has set examples in infrastructure networking through the creation of virtual centers. These unite university and industry resources and alleviate the need for new buildings and staff for research programs. The European Union also promotes access to and utilization of large infrastructure by requiring its member states to pay annual dues for these facilities. The national governments therefore have an incentive to strongly encourage their researchers to work in manufacturing, in expectation of the best possible outcome for their investment. On the other hand, the government of Japan, according to a WTEC report on MEMS technologies [1], funds infrastructure directly, as opposed to individual faculty members' research projects. Japan has extensive facilities for specialty microelectronic part-building from a variety of materials, not just by traditional silicon-based lithography for integrated circuits; it also leads in manufacturing of microscale devices by assembly.

CENTERS

Over the past decade, several Federal agencies have established and supported individual research centers in nanotechnology. Centers with particular focus on issues related to nanomanufacturing are listed below (pp. 26-27). *The National Science Foundation* (NSF) has funded a number of Engineering Research Centers, Industry-University Cooperative Research Centers, Science and Technology Centers, and Materials Research in Science and Engineering Centers related to manufacturing at the nanoscale. In the broader context of the NNI, NSF also supports 17 Nanoscale Science and Engineering Centers (NSECs) and the National Nanofabrication Infrastructure Network (NNIN), with thirteen nodes. The NNIN is focused on developing and providing broad access to state-of-the-art nanoscale fabrication, characterization, and informatics facilities for the use of industry, academic, and government researchers, with the additional goal of educating a new generation of scientists and engineers skilled in the use of such facilities. See <http://nnin.org> for more information and a complete list of participating sites.

The Department of Energy, in addition to supporting existing nanoscale manufacturing resources in its national laboratories, has also initiated five dedicated Nanoscale Science Research Centers that will provide the nation's research community with resources for the synthesis, processing, fabrication, and integration of materials at the nanoscale. These include atomic probe microscopes, instruments for single-molecule spectroscopy, etc., and are co-located with other complementary facilities that include X-ray, neutron, and electron sources as well as high-performance computers. Sandia National Laboratories has broken ground on its largest capital investment ever, the Microsystems and Engineering Sciences Applications (MESA) facility for heterogeneous micro/nanosystems development.

The National Institute of Standards and Technology (NIST) completed its Advanced Measurement Laboratory (AML)—part of which is a shared-user facility—in 2004. It provides an unprecedented combination of features designed to virtually eliminate environmental interferences that undermine research at the nanoscale. Semiconductor processing equipment and other instruments enable NIST

and its partners to fabricate prototypes of new test structures, electronic devices, standard reference materials and other measurement aids, as well as other tools for nanotechnology product and process applications. The NIST Center for Neutron Research (NCNR) also serves a large user community. The NCNR generates high-quality beams of neutrons, which are becoming increasingly indispensable research tools in a variety of fields, including many aiming for future nanotechnology applications. Nondestructive, highly penetrating probes, neutrons are useful for studying the structure, properties, and dynamics of materials of many types—from DNA and proteins to superconductors and nanocomposite coatings.

NSF-FUNDED CENTERS CONTRIBUTING TO NANOMANUFACTURING

In addition to the 13 NNIN user facility nodes mentioned above, the following are examples of NSF-funded centers contributing to manufacturing at the nanoscale:

Engineering Research Centers (ERCs)

- NSF/SRC Center for Environmentally Benign Semiconductor Manufacturing (University of Arizona)
- Center for Particle Science and Technology (University of Florida)

Industry/University Cooperative Research Centers (I/UCRCs)

- Center for Precision Metrology (University of North Carolina Charlotte)
- Center for Lasers and Plasmas for Advanced Manufacturing (Old Dominion University)
- Center for Advanced Studies in Novel Surfactants (Columbia University)
- Ceramic and Composite Materials Center (University of New Mexico and Rutgers University)
- Center for Advanced Polymer and Composite Engineering (Ohio State University)
- Cooperative Research Center in Coatings (University of Southern Mississippi and Eastern Michigan University)
- Particulate Materials Center (Pennsylvania State University)
- Center for Biocatalysis and Bioprocessing of Macromolecules (Polytechnic University)

Materials Research Science and Engineering Centers (MRSECs)

- Center for Quantum and Spin Phenomena in Nanomagnetic Structures (University of Nebraska)
- Center for Nanoscale Science (Pennsylvania State University)
- Center for Materials for Information (University of Alabama)
- Materials Research Science and Engineering Center (University of Chicago)
- Center for Chemical Assembly of Thin Films Using Nanoparticles (Columbia University)
- Materials Research Science and Engineering Center (MIT)
- Center on Polymer Interfaces and Macromolecular Assembly (Stanford University)

Science and Technology Centers (STCs)

- Center for Embedded Networked Sensing (UCLA)
- Nanobiotechnology Center (Cornell University)

Nanoscale Science and Engineering Centers (NSECs)

- Center for Scalable and Integrated Nanomanufacturing (UCLA, UC Berkeley, University of North Carolina at Charlotte, UC San Diego, Stanford University)
- Center for Nanoscale Chemical-Electrical-Mechanical-Manufacturing Systems (University of Illinois at Urbana-Champaign, Caltech, and North Carolina A&T State University)
- Center for High-Rate Nanomanufacturing (Northeastern University, University of Massachusetts Lowell, University of New Hampshire)
- Center for Affordable Nanoengineering of Polymeric Biomedical Devices (Ohio State University)
- Templated Synthesis and Assembly at the Nanoscale (University of Wisconsin Madison)
- Center for Hierarchical Nanomanufacturing (University of Massachusetts Amherst)

These nanoscience and 2D nanofabrication facilities are now being integrated into a complete, comprehensive, and versatile nanomanufacturing infrastructure network, including both the NNIN described above and the National Nanomanufacturing Network, funded by NSF in coordination with NIST and DOD. This complements the existing centers with new collaborations focusing on nanomanufacturing building blocks; coatings and surfaces; consolidates and composites; biochemical dispersions and structures; processing and integration; systems architectures; modeling tools and instruments; electronic/magnetic systems; photonics and optics; biodevices and systems; and environmental, energy, health, and safety systems. The necessity for such nanomanufacturing facilities was suggested by the research community in a number of workshops with participation of the Federal agencies, small businesses, and the European Commission, in order to support evolving needs for discovery, innovation, and applications of nanotechnology. The new facilities will feature new instrumentation and machinery with emphasis on 3D manufacturing, scale-up integration, measurement and metrology, and modeling and control of both top-down and bottom-up manufacturing technologies. The networked facilities must be designed to broaden participation of academia, industry, and Federal laboratories through geographical distribution and cyberspace teleoperation (telefabrication and telecharacterization) of the equipment. This infrastructure is intended to foster interdisciplinary research, education, and training of the workforce integrated at all levels, and opportunities for engaging the social sciences and addressing the societal impacts of nanomanufacturing.

Table 5.1
Key Collaborative Nanomanufacturing Activities (Existing and Recommended)

Collaborative Activities/Agreements	Agencies, Private Sector*
Interagency Working Group on Manufacturing Research and Development	USDA, DOC/TA, DOC/NIST, DOD, DOEd, DOE, NIH, DHS, DOL, DOT, NASA, NSF, SBA, OMB, OSTP
Industry-university-Federal laboratory collaborations for manufacturing	NSF – GOALI; NIST; DOE – CRCD
Extend international activities focused on fundamental and applied research	All agencies; World Technology Evaluation Center (WTEC) studies
Professional societies	ASME/IEEE roadmaps; SME, AVS; NCMS studies
Microelectronics Advanced Research Corp. (MARCO) focus-center model	SIA; DARPA; industry
Complementary funding between NSF and mission-oriented agencies	NSF-Sandia; NSF-DOE (Plasma Science); NSF-EPA; NSF-NIST
MOU on Research Programs in Silicon Nanoelectronics	NSF-SRC
Hierarchical nanomanufacturing	NSF – 4 NSEC centers; DOD – 1 MURI; NIST – AML
NNI-Electronics Industry Collaborative Board for Advancing Nanotechnology (CBAN)	NNI, SRC-SIA
NNI-Chemical Industry CBAN	NNI, chemical industry, individual companies
Small Business Innovation Research & Small Business Technology Transfer (SBIR/STTR) programs	All Federal R&D agencies, small companies

* See Appendix E, Glossary, (pp. 53-55) for list of agency acronyms.

REFERENCE

1. R. T. Howe, M. G. Allen, A. A. Berlin, E. E. Hui, D. J. Monk, K. Najafi, M. Yamakawa, *WTEC Panel Report on Microsystems Research in Japan* (World Technology Evaluation Center, Baltimore, MD, 2003; <http://www2.wtec.org/mems1/>).

6. PRIORITIES AND CONCLUDING REMARKS

The full spectrum of manufacturing activities at the nanoscale must be fostered by step-by-step development and maintenance of a backbone of strategically selected priority scientific and engineering R&D topics where there are opportunities for nanomanufacturing applications. These R&D and manufacturing areas should be chosen and coordinated to build upon each other in a causal succession, to capitalize on present and anticipated nanotechnology developments in the laboratory, to balance the required resources for their support, and to optimize their service to society and national needs in a timely fashion.

SHORT-TERM (1–5 YEARS) PRIORITY AREAS AND MODES OF SUPPORT

- Systematic methods for synthesis and fabrication of a broad spectrum of products through manufacturing at the nanoscale; development of nanomanufacturing technologies and tools for high yield and high productivity. (High yield and high productivity are among the critical issues that will make nanoscale processes commercially viable.)
- Development of an integrated network that takes advantage of the university system in order to attract and educate the future generation of nanoscale manufacturing scientists and engineers, as well as to train the new professional workforce needed in nanotechnology industries, from all over the world. The National Nanomanufacturing Network, recently launched by the UMass Amherst NSEC in cooperation with other NSECs, NIST, DOD, and other nanomanufacturing R&D stakeholders, represents an initial step towards accomplishing that goal.
- Centers large enough to integrate the various expected critical components of nanoscale manufacturing such as bottom-up assembly of nanostructure building blocks, top-down fabrication techniques, fabrication of hierarchical multiscale structures with atomic precision, nanolithographic patterning, and biomimetics.
- Nanoscale metrology accepted by national and international organizations, enabling global markets.
- Development of know-how and data permitting an informed evaluation of the economic, safety, and environmental implications of nanoscale manufacturing processes and products.
- Certified education/training programs integrated with nanomanufacturing research.
- Development of data on materials, processes, and equipment properties necessary for creating “smart machines”—measurement and self-correction for quality control, ultimately capable of predicting properties of manufactured parts.
- Combining of scientific understanding and technological innovation now underway in universities and national laboratories with technology and manufacturing in the marketplace.
- Small Business Innovation Research (SBIR), Small Business Technology Transfer (STTR), Advanced Technology Program (ATP), and Manufacturing Technology (MANTECH) projects and/or company, university, and national laboratory partnerships to accelerate transition of science discovery into manufacturing technology.
- Workshops and conferences to share new nanotechnology opportunities among research, manufacturing, and financial interests in order to promote partnerships, synergism, and realistic expectations.
- Establishment of mechanisms for review and assessment of NNI program performance to manage risks and evaluate effectiveness of funded programs.

THE ROLES OF NANOSCALE MANUFACTURING

- Enable a new world of technologies, products, and services that are not possible otherwise
- Address issues of general public interest such as increasing work efficiency, healthcare technology, occupational health and safety, and protecting and improving the environment
- Support traditional industry with new enabling technologies and establish new, nontraditional manufacturing ventures and markets
- Rekindle manufacturing growth in the United States, offer new employment opportunities, and broaden participation in and geographic distribution of activities and resources
- Establish the United States as the international leader in modern and advanced manufacturing

CONCLUDING REMARKS

Beyond research and education enterprises, the investment in nanoscale manufacturing infrastructure aims to generate completely new industry sectors in manufacturing a multitude of nanoscale devices and products and in offering associated services in their design, fabrication, integration, and use. This investment offers the opportunity to recapture the U.S. share in global markets for high-technology manufacturing, such as that enjoyed by the U.S. automotive industry in the first half of the 20th Century. An advanced nanomanufacturing infrastructure network would attract discoveries and ideas from all around the world for analysis, implementation, and eventual benefit to the national economy and society. Nanomanufacturing promises to open up new markets and help revitalize the national economy. At the same time, a selective, geographically distributed investment in nanomanufacturing infrastructure can offer well-balanced technical and economic development. This will broaden its benefits to all regions and promote the participation of diverse population groups. Such infrastructure will therefore provide a critical link in delivering the promise of the National Nanotechnology Initiative, “...to change the way almost everything—from vaccines to computers to automobile tires to objects not yet imagined—is designed and made” [1], and to improve our quality of life in its numerous aspects, from consumer products to health services.

REFERENCE

1. National Science and Technology Council, *National Nanotechnology Initiative: The Initiative and its Implementation Plan* (NSTC, Washington, D.C., 2000; <http://www.nano.gov/html/res/nni2.pdf>).

APPENDIX A. WORKSHOP AGENDA

Grand Challenge in Manufacturing at the Nanoscale

May 13, 2002

National Science Foundation
4201 Wilson Blvd., Arlington, VA

1:00–1:30	<i>Welcome and Introduction</i> Mike Roco, NSET; Clayton Teague, NIST [§]
1:30–1:45	<i>Nanoimprint Lithography (NIL) and Lithographically-Induced Self-Assembly (LISA) –Low-Cost and High-Throughput Nano-Manufacturing</i> Stephen Chou, Princeton University
1:45–2:00	<i>Challenges for Manufacturing Nanoelectronics</i> Robert Doering, Senior Fellow, Texas Instruments
2:00–2:15	<i>Synergy of Top-Down and Bottom-Up Approaches for Nanofabrication</i> Michael Heller, Nanogen and University of California, San Diego
2:15–2:30	<i>Nanomanufacturing for Next Generation Engineered Systems: Materials, Tools, Processes, and Workforce</i> Ajay Malshe, ASME and University of Arkansas Avram Bar-Cohen, ASME and University of Maryland
2:30–2:45	<i>21st Century Collaboration Models for Nanomanufacturing</i> Manish Mehta, Executive Director of Industry Forums, National Center for Manufacturing Sciences
2:45–3:00	<i>Coffee Break</i>
3:00–3:15	<i>Manufacturing Needs of Nanofabrication and Nanostructures</i> Sandip Tiwari, Cornell University and NNUN
3:15–3:30	<i>Nanomanufacturing: Issues in Taking Nanotechnology Mainstream</i> Judith Todd, Penn State University
3:30–3:45	<i>Other Individual Statements</i>
3:45–5:00	<i>Panel Discussion</i> Haris Doumanidis, NSF; Clayton Teague, NIST; Mike Roco, NSET
5:00–5:30	<i>Reception and Adjournment</i>

§ Affiliations shown here are as of May 2002.

APPENDIX B. EXAMPLES OF NANOSCALE PRODUCTS, MANUFACTURING TOOLS, AND PROCESSES

The following is a selection of nanotechnology products and processes that are commercially available or under development by small and large companies. This list is not intended to be exhaustive, however, it is illustrative of the broad range of applications that are being, and will be, addressed using nanomanufacturing.

Transparent Nanopowder Dispersions (Medwing/Elta Block)

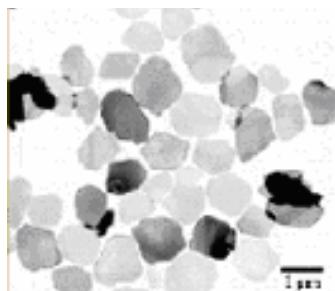


Figure B.1. ZnO powder dispersion in a sunscreen (courtesy of Medwing/Elta Block).

New mechanical grinding, milling, alloying, mixing, and dispersion technologies have been transferred to production of nanopowder-laden dispersions and suspensions, such as creams for pharmaceuticals and beauty products. These methods, employing surface functionalization and electrical charging of particulates, cope with problems of aggregation of the nanopowders into clusters, and thus minimize the effective size and maximize the active surface area of the particles. An example is sunscreen creams (Fig. B.1) with dispersed ZnO and TiO₂ nanoparticles (about 100 nm dia.), which absorb and scatter ultraviolet radiation twice as effectively as traditional products while minimizing interference with visible wavelengths, thus resulting in

a transparent ointment preserving the original appearance of the substrate. Other applications include paints, additives, and varnishes.

Molded Nanocomposites for Automotive Parts (GM)

Much progress has been made in industrial production of automobile parts made of injection-molded polymer nanocomposites with clay nanofillers (Fig. B.2). This has been extended to low-cost thermoplastic polyolefin (TPO) resins that previously were reinforced with microscale talc particles, glass, or carbon fibers. New manufacturing technologies have enabled the exfoliation of smectite clay fillers into nanoflakes about 1 nm thick and 100-1000 nm long, as well as their dispersion in the polymer, avoiding aggregation phenomena and thus maximizing the interaction surface with the matrix and the reinforcing effects. Thus, low smectite filler contents (2.5-3%) of TPO nanocomposites can yield up to 20% weight savings at similar stiffness (1000-1200 MPa) and improved low-temperature ductile strength compared to traditional TPO composites (with 15-20% talc content) of the same cost. The nanocomposites display improved throughput, paint adhesion, and recyclability because of the smaller filler amount. The production of nanocomposite parts uses injection molding at lower pressure and reduced cycle times compared to conventional composites.



Figure B.2. Nanocomposite step-assist for vans (courtesy of GM/Blackhawk Automotive Plastics).

Abrasion-Resistant and Hermetic Nanocomposite Coatings (Triton)

Nanocomposite polymer coatings with nanopowder additives are commercially co-extruded or bonded to a variety of substrate materials (Fig. B.3), providing up to four times the abrasion resistance of conventional scratch-proof coatings. Cross-linking and reinforcement mechanisms of the polymer chains of the coating matrix by the nanoparticulates enable these coatings to withstand mechanical ploughing and chemical action effects. At the same, the nanoparticle size and dispersion control selective absorption and scattering of visible light, providing clear coatings with customized optical properties, i.e., anti-reflection and tailored refractive indices, with applications in helmet visors, aircraft canopies, and smart windows. Besides impact resistance, the same mechanisms in such nanocomposites also yield improved oxygen and moisture diffusion barriers, making them suitable for hermetic food and beverage packaging.



Figure B.3. Nanocomposite coatings in helmet visors, pharmaceutical packages, and food containers (courtesy of Triton Systems, Inc.).

Liposome Nanocapsules in Cosmetic Lotions (L’Oreal)

Since the 1970s the cosmetics industry has been producing liposome lotions for delivery of active ingredients to the skin strata. Liposomes are capsules ranging between 130 and 600 nm in size, consisting of a tiny polymeric shell filled with nanoparticles (Fig. B.4)—fluid ingredients such as vitamin A, retinol, and β -carotene—to effectively deliver their anti-aging and nutrition properties to the deeper skin layers. The shell is coated with biodegradable polymers that are removed by natural enzymes once the capsule is in the skin, thus releasing the active ingredients in the lower strata of the skin. The nanoparticles included in the capsules are ground under high pressure to 50–60 nm, yielding a translucent product suggesting purity and cleanliness.



Figure B.4. Nanocapsule shell structure in lotion (courtesy of L’Oreal).

Carbon Nanotube Fiber Fabrics and Nanocomposites (University of Texas at Dallas, Babolat)

Besides lower-cost mass production of carbon nanotubes (e.g., via hydrocarbon decomposition by liquid-phase self-regulated arc discharge), progress has been made towards fabrication of fibers out of water suspensions of polyvinyl alcohol (PVA) strands wrapped around carbon nanotube bundles (Fig. B.5). Key to this development is manufacturing of sufficiently long fibers by a gel drawing

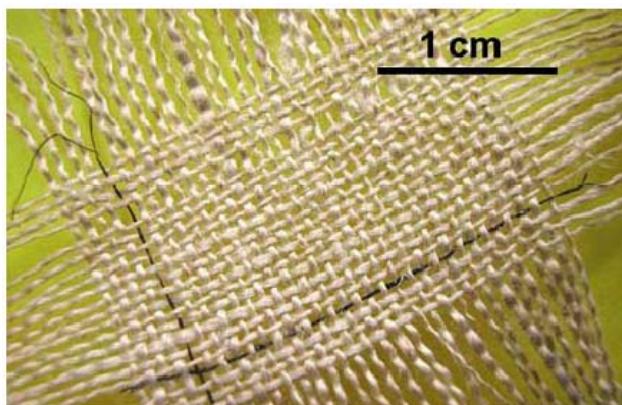


Figure B.5. A textile containing two carbon nanotube-fiber supercapacitors (each consisting of a twisted pair of fibers) woven in orthogonal directions (courtesy of R. Baughman, UT/Dallas; © 2003 Macmillan Publishers, Ltd., <http://www.nature.com>; reprinted by permission from [1]).

properties. The cost of carbon nanotube manufacturing is still the limiting factor for such applications.

Nanocomposite Dental Filling Materials (3M-ESPE)

The needs for stronger dental materials and improved polishing mechanisms are key motivations for the present introduction of nanocomposite filler materials to the dental industry. Nanoparticles in filler composites minimize interference with the longer visible light wavelengths, thus creating materials that to the human eye are aesthetically indistinguishable from natural tooth structure (Fig. B.6). At the same time, the nanoscale particle size yields improved polishability compared to microhybrid composites containing 0.4–0.6 micrometer-sized particulates, while still maintaining excellent mechanical properties suitable for high-stress-bearing restorations. Besides initial polish, superior polish retention results (typical of microfills) are obtained from the smaller crater and protrusion asperities generated by material wear in service, thus ensuring longer-lasting luster of dental fillings.

process through spinning pipe orifices assisting the fiber coalescence [1]. The resulting carbon nanotube-reinforced fibers display toughness 4 times higher than spider silk and 17 times higher than Kevlar, and higher tensile strength than that of steel wires, which makes them suitable for impact-proof barrier fabrics. These are also electrically conductive and could power connected electronics, sensors, and communication devices. Fibers in twisted-pair arrangements also exhibit supercapacitor behavior for storage of electric charge in energy systems. In addition, carbon nanotubes are presently integrated with graphite fibers in nanocomposites for sporting goods such as tennis rackets, with high stiffness and custom shock absorption



Figure B.6. Comparison of a microhybrid (top) and nanocomposite (bottom) dental filling (courtesy of 3M-ESPE Filtek Supreme Universal Restorative).

1. A. B. Dalton, S. Collins, E. Muñoz, J. M. Razal, V. H. Ebron, J. P. Ferraris, J. N. Coleman, B. G. Kim, R. H. Baughman, Super-tough carbon-nanotube fibres, *Nature* **423**(6941), 703 (2003).

Fire-Retardant Barrier Nanocomposites (Southern Clay Products)

The introduction of nylon-matrix nanocomposites with montmorillonite clays (MMT) in the late 1980s was followed by development of several specialty materials. In the original nanocomposite,

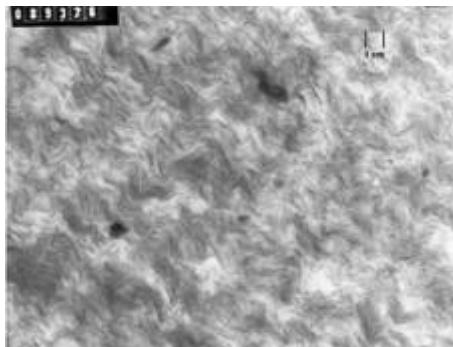


Figure B.7. Nylon-MMT nanocomposite (courtesy of Southern Clay Products, Inc.).

MMT (a layered aluminosilicate clay) nanoflakes just 1 nm thick were dispersed at <5% filler weight (compared to typical 30% of talc and glass reinforcements) in nylon 6 resin (Fig. B.7), greatly improving mechanical strength, heat resistance, and dimensional stability, as demonstrated in engine timing belt cover applications. Besides improved appearance and recyclability due to the smaller filler loadings, nanocomposites with clay fillers have improved gas barrier properties (over 3 times better for oxygen, compared to unfilled nylon), making them appealing for packaging applications. In addition, since nanodispersed MMT clays appear to be char-forming catalysts

making non-char-forming polymers such as polystyrene to form char, the nanocomposites exhibit improved fire retardancy and reduced flammability. Further research is underway on manufacturing aspects such as MMT exfoliation during polymerization, melt processing, or solvent dispersion during melt blending of the resin.

Silver Nanocoating and Nanoparticle Sterilization (Samsung)

The well-known disinfectant and antibiotic properties of silver are being exploited in Ag^+ nanoparticle form, with large active surface area, for sterilization in special washing machines for laundry loads that are heavily biologically stained from bacteria and mold (Fig. B.8). The inside of the power drum is covered with a silver-particle-laden nanocoating with disinfection action, while the silver sterilization system of the machine generates and dispenses Ag^+ nanoparticles to the laundry during the rinse cycle. A self-cleaning filtering function completely removes the particles from the tub after the end of the laundry cycle. The silver sterilization washing machine has been shown to kill 99.9% of bacteria without bringing the laundry to boil, therefore reducing energy and detergent requirements and contributing to environmental and health protection.

Nanoscale Imprinting Lithography (Molecular Imprints Inc., Nanonex Corp.)

Mechanical imprinting nanolithography methods, through contact printing and embossing under proper temperature and pressure, can stamp or impress nanoscale patterns with features as small as 10 nm on heat-hardenable or ultraviolet-curable materials, and can provide a lower-cost alternative to diffraction-limited photolithography processes for manufacturing of microelectronics, MEMS,



Figure B.8. A silver sterilization washing machine (courtesy of Samsung Electronics).

biofluidic devices, etc. Such methods include nanoimprint lithography (NIL), step and flash imprint lithography (SFIL) (Fig. B.9), nano-transfer printing (nTP), etc. Commercial systems are already on the market and have been tested in production applications. At the same time, research is underway to resolve the requisite needs for surface planarity and layer alignment, pressure in multilayer structures, and rheological and surface adhesion between the solid master and the imprinted resin in high aspect ratio structures. This is necessary to demonstrate production rates and quality control needed for competitive industrial production.



Figure B.9. An SFIL machine (courtesy of Molecular Imprints, Inc.).

Nanocoated Self-Cleaning Glass (PPG Industries)

The PPG self-cleaning glass features a coating with photocatalytic and hydrophilic properties. The durable and transparent coating consists of nanostructured titanium dioxide (TiO_2), which is integrated with the hot glass during its manufacturing process into a long-lasting product. The photocatalytic properties of the coating are energized by UV illumination and gradually disintegrate and loosen organic dirt deposited on the glass. The hydrophilic properties reduce surface tension and lead to sheeting rather than beading of water on the glass, which helps flush the surface clean and accelerate drying, leaving the glass with minimal spotting and streaking (Fig. B.10). Self-cleaning glass is manufactured in standard and energy-saving panels with controlled transparency for windows.

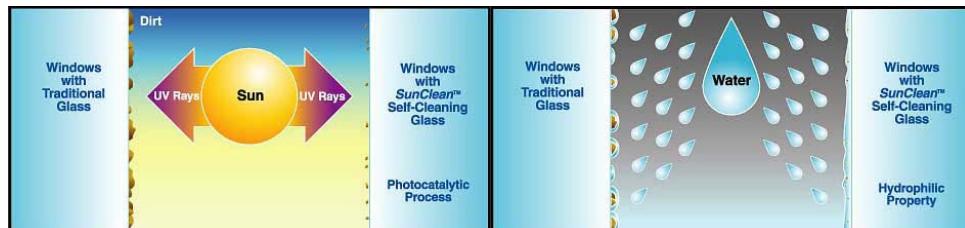


Figure B.10. Photocatalytic and hydrophilic processes in self-cleaning of glass (courtesy of PPG).

Mesoporous Catalyst Materials by Liquid Crystal Templating (ExxonMobil)

For mesoporous catalyst substrates with pores larger than 1.3 nm, zeolites and zeolite-like materials have reached their stability limits. In 1992 the synthesis of a new class of mesoporous material (MCM-41) molecular sieves was presented. MCM-41 materials (Fig. B.11) are amorphous, hexagonally packed silicates and aluminosilicates with a uniform, honeycomb-like channel structure. The diameter of these channels can be adjusted between ~ 1.6 to 10 nm during synthesis, yielding surface areas reaching ~ 400 to more than $700 \text{ m}^2/\text{g}$. Their production is achieved by self-assembly of amphiphilic surfactants in micelles as structure-directing elements in a liquid crystal templating sol-gel process. The micelles are encapsulated by the inorganic material balancing the micelle charge, and the organic surfactant is finally removed by thermal calcination.

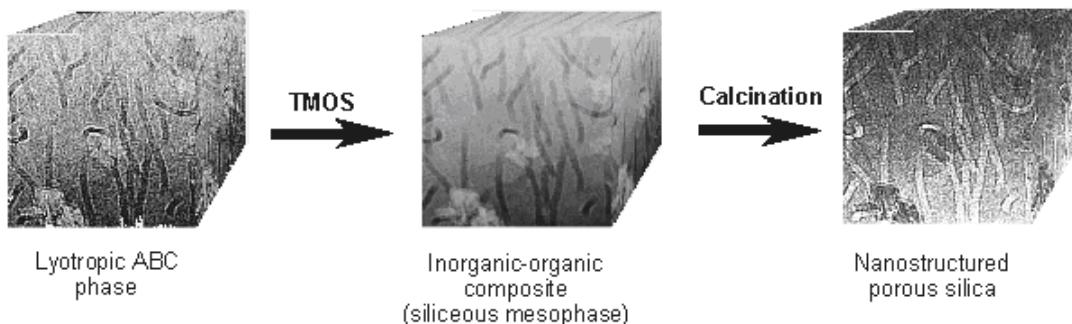


Figure B.11. MCM-41 fabrication and mesoporous structure (courtesy of ExxonMobil).

Electron Beam Lithography Fabrication Integrated to Electronic Microscopy (Raith)

Widely available electron microscopes and focused ion beam instruments can be adapted to fabricate master patterns with nanoscale features, which are useful for mass manufacturing via nanoimprinting and patterned bottom-up assembly. Add-on packages allow scanning electron microscopes (SEMs) or transmission electron microscopes (TEMs) to be used for electron beam lithography (EBL), and focused ion beams instruments to be used for ion beam lithography (IBL). EBL and IBL nanowriting can be combined with in-process, *in situ* nanoscale imaging in small-scale step-and-repeat exposures to dramatically enhance real-time process monitoring and control while improving resolution, repeatability, and fabrication rates of tools and devices (e.g., quantum wire structures, quantum well structures, and transistor prototypes).

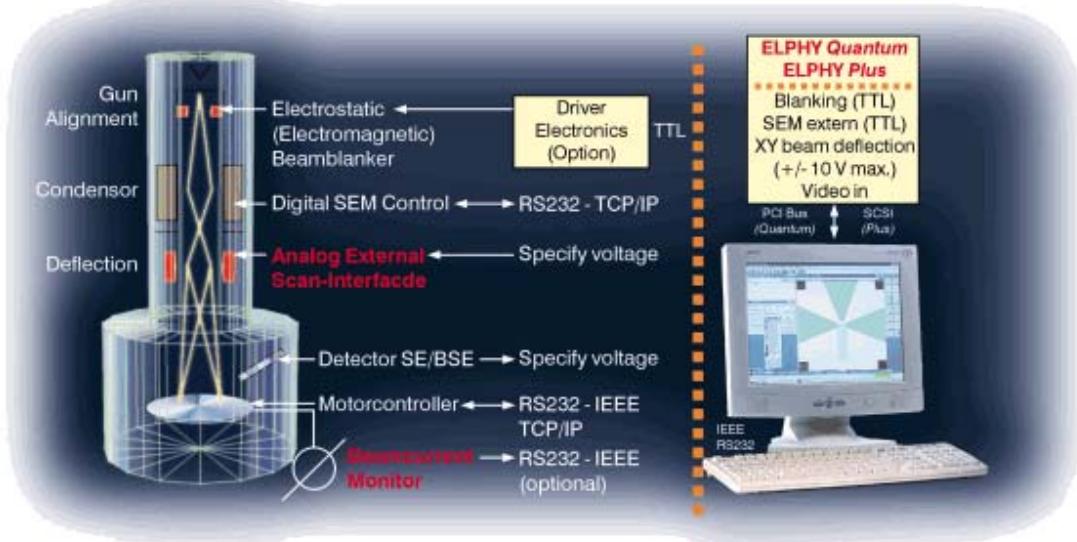


Figure B.12. An SEM/EBL system (courtesy of Raith GmbH).

Probe Array Nanofabrication (IBM)

Large arrays of cantilever probes that thermomechanically induce indentations in thin polymer films, such as the IBM Millipede project (Fig. B.13), have been developed and used for ultrahigh-density data storage (1 trillion bits per square inch in pilot testing, equivalent to 25 DVDs on a postage stamp area, and 20 times higher density than magnetic storage). Prototype 2D arrays feature over 4000 (64 x 64) V-shaped tips (2 μm long) on 70 x 0.5 μm Si cantilevers, arrayed over a 7 mm^2 field. Each tip produces indentations 10 nm in diameter through resistive heating and deformation of thermoplastic films, at kHz to MHz frequencies and very low power consumption. The arrays feature accurate leveling, vibration damping, and good addressability in two dimensions with respect to the processed medium, as well as time-multiplexed electronics for addressing the probes. Besides its suitability for high-resolution and high-rate, flexible, continuous patterning, the Millipede technology also features reversible erasing/rewriting capabilities for dynamic reshaping and error correction, as well as thermoresistive in-process sensing of the surface topology, making it appealing as a generic planar nanostructure fabrication tool with feedback control. Potential applications include masterless thermomechanical nanolithography, atomic and molecular quantum nanomanipulation, and large-area nanoscopic imaging.



Figure B.13. Millipede nanopatterning (courtesy of IBM Zurich Research Laboratory; unauthorized use not permitted).

GMR-Based Magnetic Random Access Memory (MRAM) (Motorola, Freescale Semiconductor)

In the 1950s computers used ferrite core magnetic memories. They were nonvolatile, but relatively slow, bulky, and power-hungry. Semiconductor memories relegated them to the junkyard, even though the semiconductor memories lost their information when electrical power was turned off. The development of molecular beam epitaxy for magnetic metals in the mid-1980s led to the

discovery of the giant magneto resistance (GMR) effect in superlattices of nanoscale thin films. IBM rapidly adapted this phenomenon to replace magnetic memory read head technology (late 1990s); in turn, this enabled magnetic memory to reach its present density of ~ 10 gigabytes/cm².

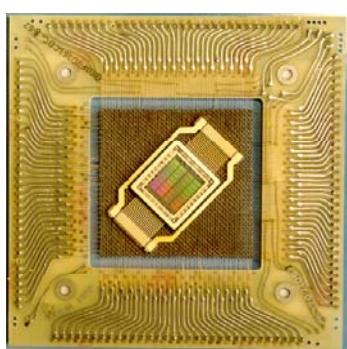


Figure B.14. GMR/MRAM memory (4 Mbits with 10 ns access time) (courtesy of Motorola).

In 2004, leveraging DARPA funding in GMR, Motorola introduced commercial dynamic random access memory (DRAM) with 4 megabits capacity and 10 ns access time (Fig. B.14), reintroducing magnetic memory to the market some 50 years after the demise of

ferrite core memory. Compared to the ferrite technology, the GMR memories are 10^3 times smaller, with 10^3 times faster access time, and with 400 times less power demand.

Nonvolatile Carbon Nanotube Random Access Memory (Nantero)

Carbon nanotubes have a combination of properties that give them the potential to be highly valuable for use in electronics applications: They have higher electrical conductivity than copper or gold, higher thermal conductivity than diamond, higher tensile strength than steel, and of course a very small size (diameter on the order of 1 nm in the case of single-walled carbon nanotubes).

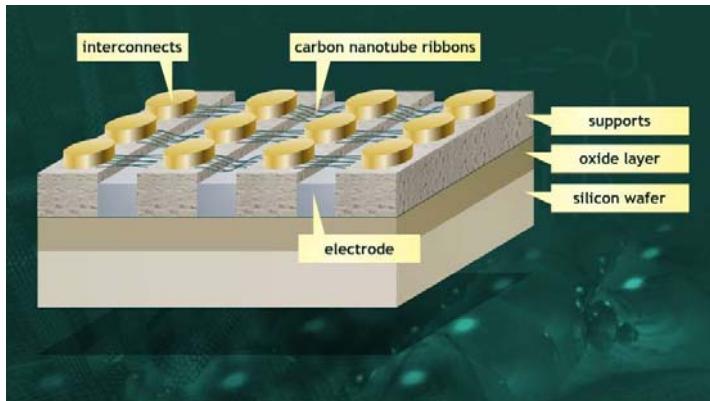


Figure B.15. Platform for nanoelectronics using carbon nanotubes (schematic of the NRAM design) (courtesy of Nantero).

However, there are substantial barriers to using them in a mass production process. Their properties are hard to control, they cannot be easily positioned or placed or aligned, and they are generally available only with substantial particulates and contaminants included. Solutions have been developed that may allow carbon nanotubes to be used in a production CMOS process in any existing semiconductor fab.

Nonvolatile random access memory (NRAM™) (Fig. B.15) is a form of memory that could replace flash memory, dynamic RAM (DRAM), static RAM (SRAM), and ultimately hard disk storage—in other words, *universal memory*. NRAM™ has the following characteristics: permanently nonvolatile like flash memory, faster than DRAM, smaller cell size than DRAM, lower power consumption than DRAM, as portable as flash memory, unlimited read/write cycles (unlike flash memory), and high resistance to environmental forces (e.g., heat, cold, magnetism, alpha particles, radiation).

Nonwoven Fabrics from Electrospun Nanofibers (eSpin)

Electrospinning of plastic and ceramic nanofibers, through a rheological instability of charged polymer melt droplets in an intense electrostatic field, has been scaled to industrial production of nanofiber products. The nanofibers, featuring 10-100 nm diameters and macroscale lengths, are 2-3 orders of magnitude finer than traditional textile fibers and human hair and can be made of a variety of nylon, polyesters, polyamids, acrylics, etc., as well as biomolecules such as proteins or collagen. Randomly laid aggregates of nanofibers in nonwoven bundles, membranes, and bulk structures exhibit high porosity, small interstitial size, and high surface area resulting in high absorbency, and reactivity to chemically functional groups. Typical applications of nanofiber threads and paper-like membranes are in barrier fabrics, filtration products, and biomedical devices. These are used for thermal insulation, energy storage, lightweight structural composites, high-retention filters, and potential bandage and diaper products (see Fig. 2.2, p. 6).

Atomic Force Microscopes in Process Control (Veeco)

Following the introduction of scanning tunneling microscopy (STM) in 1981 by Binnig and Rohrer, atomic force microscopy (AFM), invented in 1986, has evolved to play a key role in nanotechnology laboratories including in biology, life, and material sciences. Because it does not require ultrahigh vacuum or cryogenic temperature environments, the AFM is also evolving into a practical quality control tool in manufacturing industry (Fig. B.16), including in the manufacture of nanocoatings, nanocomposites, and semiconductors. Sampled statistical process control (SPC) is in use by chip manufacturers to analyze the wafer surface for defects before the next step of the production process, using AFM surface profiling and leading to productivity improvement in semiconductor manufacturing automation applications. Current research also focuses on defect management and repair using the nanomanipulation capabilities of the AFM.



Figure B.16. An AFM configuration (courtesy of Veeco Metrology).

Nanomanipulator Systems (Zyvex)

A fundamental requirement for both laboratory sample analysis and processing, as well as for industrial fabrication of nanostructures requiring precision alignment and registration, is nanoscale positioning and orientation by a nanomanipulator system (Fig. B.17). Four degrees of freedom

precision nanomanipulators, based on honeycomb drive or piezoelectric MEMS yielding positioning resolutions in tens of nanometers and rotary resolutions down to 10 microrads, are commercially available, while full 6 degree of freedom systems are under development. These nanomanipulators are controlled by computers and are compatible with standard electronic, optical, or probe microscopes for sample manipulation. Other applications include nanoscale testing rigs for use in measuring mechanical properties such as elastic modulus, resonant frequency, and friction coefficient, as well as in nanoprocessing such as separation and joining of nanostructures.

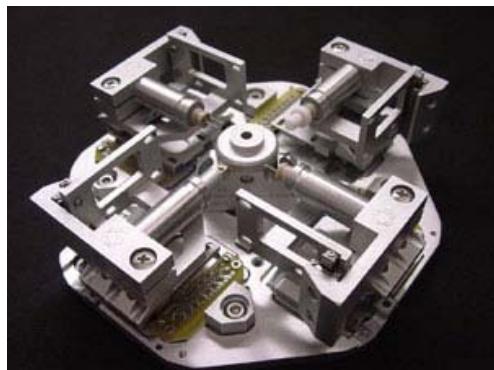


Figure B.17. A nanomanipulator system (courtesy of Zyvex).

Three-Dimensional Integrated Nanophotonic Circuits

Photonic crystals [2] are multidimensionally periodic dielectric structures that can control electromagnetic waves in a manner analogous to the way band structures of semiconductor crystals control electron waves. The concepts of band structure carry over to photons, and the creation of a photonic bandgap is a starting point for the creation of many types of optical devices and systems. Indeed, photonic crystals are usually made of semiconductors and can exhibit both a photonic bandgap and an electronic bandgap in the same substance.

By disrupting the perfect periodicity of the photonic crystal, a nanostructured photonic crystal device (Fig. B.18) can introduce electromagnetic cavities, waveguides, modulators, and other components [4]. A photonic modulator can be made by carrier injection or depletion in a 3D optical resonator cavity [5]. Injection would detune the resonator and spoil the critical coupling and the cavity transmission due to free carrier absorption. By turning off the bias, the carriers can be totally depleted, restoring a perfect high Q cavity. This modulation can be very efficient, with the biased state blocking light and the normal state transmitting. Such optical nanostructures can be the basis of a nanoscopic photonic integrated circuit technology that is rooted in the economics, miniaturization, and process technology of conventional integrated circuits. As a long-term goal, it could enable the development of an integrated optical computer.

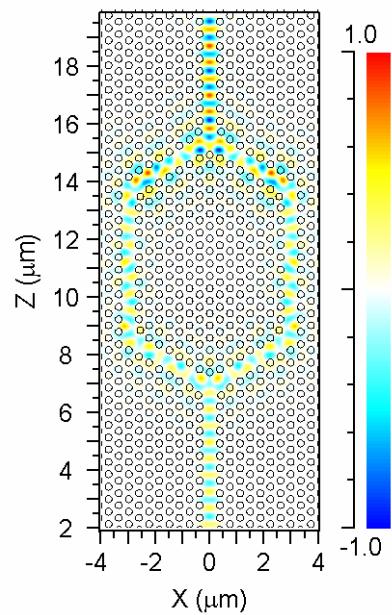


Figure B.18. Example of a Mach-Zehnder device fabricated using photonic-crystal waveguides (© IEEE; reprinted by permission from [3]).

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Drug and Gene Sequencing Arrays (Nanogen)

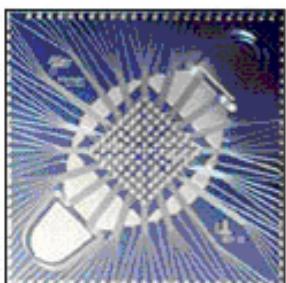


Figure B.19. A nanochip electronic microarray (courtesy of Nanogen).

Development and production of new nanostructured pharmaceuticals and biosensor nanodevices have been greatly accelerated by electronic sequencing microarrays (Fig. B.19) that are capable of rapid identification and precise analysis of biomolecules including DNA and RNA. Because of their natural electrical charging, the molecules are rapidly moved and concentrated in addressable designated sites of the chip. Such microarray nanochips are available for on-chip, non-PCR amplification (e.g., through strand displacement methods enabling exponential

amplification of DNA by an isothermal reaction), simplifying detection of low levels of the diagnostic target. They are also available in fluorescent kinase assay platforms for electronic screening applications for drug discovery of kinases, phosphatases, and proteases, with several hundred well microtiter plates, without use of antibodies or radioactivity. These enable disease diagnostics, drug discovery, novel oligonucleotide chemistries, as well as forensic applications via genetic-based *in vitro* human detection and biowarfare agent detection.

Sintering of Nanoceramics and Nanocomposites by Plasma Pressure Compaction (MatMod)

A new powder consolidation technique has been developed for compaction of submicrometer-sized powders and nanopowders of metals, intermetallics, and ceramics, which also can be used as an alternative to hot isostatic pressing of micrometer-sized particles. Plasma pressure compaction (P²C) uses plasma to break surface oxide and impurity layers of sintered powders and to partially provide the activation energy for micro/nanobonding of the cleaned core material of the particulates. This results in reduction of the necessary processing temperature, which is essential to prevent grain growth in the consolidates and thus to preserve the nanoscale properties of the particulates in the part. It also improves the consolidation density and reduces oxygen and other gas contamination in the product without the need for sintering additives and precompaction of a green part. The process also can be used for reactive joining of dissimilar materials and reactive synthesis of near net shape parts, such as carbon-carbon composites for high strength/weight-ratio, temperature- and corrosion-resistant materials for engine pistons, etc (Fig. B.20). Such products can provide benefits in terms of fuel economy, maintenance, pollution, and noise prevention.



Figure B.20. (Left) P²C device (courtesy of Materials Modification, Inc.); (right) C-C composite piston (courtesy of Detroit Diesel).

Jumbotron Lamp (Saito)

Progress in manufacturing of oriented carbon-nanotube-covered surfaces by plasma enhanced chemical vapor deposition (PECVD), pulsed laser deposition (PLD), etc., has enabled harnessing of the unique electron emission properties of carbon nanotubes. In a diode configuration, a cathode ray tube (jumbotron lamp) has been commercialized (Fig. B.21), producing light by bombarding a phosphor-coated surface with nanotube-emitted electrons, featuring twice the brightness of thermionic lighting elements and lifetimes up to 8,000 hours. The required low applied voltage yields improved energy efficiency. The lamp can be used for illumination and large outdoor displays. Carbon nanotube field emitters with current densities over 0.1 A/cm^2 have been under development for microwave amplification to replace unreliable thermoelectronic emitters, and for overvoltage protection in a gas discharge tube arrangement [6]. Further research is aimed at improving manufacturing aspects of nanotube field emitters and gated triode microdevices, including lifetime, yield, and cost.



Figure B.21. A nanotube-based jumbotron lamp (© 2000 Elsevier; reprinted by permission from [7]).

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Pharmaceutical Delivery Vector Production (CytImmune)

Nanoparticle vectors with physicochemical properties promising a biotherapeutic action, such as colloidal gold, are currently manufactured for targeted delivery of biomolecules and drugs to selected cells or molecular cell structures. In colloidal gold, for example, the Au nanoparticles can act as docking sites for more than one biomolecular species (Fig. B.22), thus yielding targeted delivery of pharmaceuticals. This is now exploited for nontoxic delivery of cytokines, such as tumor necrosis factor (TNF), for immunotherapeutic treatment of cancer cells. There is also promise for selective gene delivery of DNA genetic material to the inside of specific cells.



Figure B.22. A colloidal gold nanoparticle as a drug-delivery vector (courtesy of CytImmune).

APPENDIX C. NNI NANOMANUFACTURING ACTIVITIES

CURRENT AND PROPOSED AGENCY ACTIVITIES: EXCERPT FROM THE NNI FY 2007 BUDGET SUPPLEMENT REPORT

The following is excerpted from the NNI Supplement to the President's FY 2007 Budget*. The NNI investment currently is classified under seven Program Component Areas (PCAs), of which one is Nanomanufacturing. The material included here from the NNI 2007 budget report is the section describing current and proposed NSET member agency activities with respect to nanomanufacturing.

PCA 5: NANOMANUFACTURING

NNI Agencies Requesting 2007 Funding for R&D Related to This PCA: DHHS (NIH), DOC (NIST), NASA, NSF, USDA (CSREES), USDA (FS)

Other Participating Agencies: DHHS (NIOSH), DOC (BIS), DOC (TA), DOC (USPTO), DOD, DOE, DOT, EPA, ITIC, ITC

Program Component Area 5 is focused on nanomanufacturing. Development of the capability to manufacture nanoscale materials and devices is key to realizing the potential benefits of nanotechnology for society. Nanomanufacturing is taken here to include all means that have the capability to reproducibly transform matter—from a bulk form or from individual atoms, molecules, and supramolecular structures—into nanoscale or nanostructured materials, devices, or systems with desired properties and performance characteristics, typically in large quantities.

Additionally, nanomanufacturing includes the capability to integrate such nanoscale materials and devices into systems spanning nanoscale to macroscale dimensions. NNI programs in this area support the development of nanomanufacturing capabilities, including tools and processes for the modeling, design, and manufacture of nanomaterials, nanostructures, and nanosystems. Research and development programs address new methods for design, simulation, and production that enable scaled-up and cost-effective manufacturing of nanoproducts in the expectation that nanomanufacturing will be one of the principal technologies impacting the future of manufacturing in general. As processes are scaled from laboratory prototyping to fabrication of products, reproducibility and testability become critical, as do regulatory oversight and approval processes.

President's 2007 Request

Strategic Priorities Underlying This Request

- Research into use of self-assembly, directed self-assembly, programmed self-assembly, biologically driven self-assembly, and scanning-probe-based techniques for control of matter at

* *The National Nanotechnology Initiative: Research and Development Leading to a Revolution in Technology and Industry. Supplement to the President's FY 2007 Budget* (Subcommittee on Nanoscale Science, Engineering, and Technology, Washington, D.C., July 2006; http://nano.gov/NNI_07Budget.pdf). See also at the end of this section an additional update excerpted from the FY 2008 NNI Budget Supplement.

the nanoscale, including biologically inspired processes and techniques, and research into methods for integrating manufactured nanoscale products into larger application structures

- Development of process control and quality control in manufacturing at the nanoscale based on traceable metrology
- Research and development on precompetitive nanomanufacturing problems such as scale-up and reproducibility of nanomanufacturing processes
- NSET Subcommittee coordination with other Federal efforts to enhance the manufacturing infrastructure of the United States, thereby providing jobs and other economic benefits
- Efforts to seek and utilize advice from the electronics, chemical, and other industries to sharpen the NNI program
- Development and demonstration of manufacturing processes that incorporate nontoxic constituents and that use less energy, water, and other resources

Highlights of the 2007 Request

- Continued development of the NIST Center for Nanoscale Science and Technology (CNST) and nanomanufacturing and nanofabrication programs
- Establishment of a network for nanomanufacturing based on an NSF Center for Hierarchical Nanomanufacturing, including other NSF NSECs, DOD Multidisciplinary University Research Initiative (MURI) sites, and the NIST CNST
- Identification of appropriate opportunities to introduce nanomanufacturing into the DOD Manufacturing Technology (MANTECH) program
- Establishment of multiple programs to develop new metrology and characterization tools suitable for manufacturing environments
- NSET Subcommittee participation in the National Science and Technology Council (NSTC) Interagency Working Group on Manufacturing Research and Development (IWGM)

Interagency Planning, Coordination, and Collaboration Supporting the 2007 Request

DOC (NIST, TA), NSF, DOD: Leading in establishing collaboration between the NSTC Interagency Working Group on Manufacturing Research and Development and the NSET Subcommittee.

DOD, NSF, NIST: Coordination of program plans and program reviews for development of R&D partnerships and for the nanomanufacturing R&D efforts highlighted above.

USDA, NSF: Developing new understanding of nanobiomaterials and nanobiodevices that may be integrated into novel applications in nanomanufacturing.

2006 and 2007 Activities by Agency

DHHS (NIOSH): Continue to develop and expand research, information, education, and recommendation-based programs to facilitate the integration of good occupational safety and health practices in nanomanufacturing.

DOC (NIST): Continue planning to develop the necessary instrumentation, measurement science, and standards, as well as establish the materials and process characterization needed by industry for nanoscale manufacturing. Additionally, in support of the Administration's emphasis on nanotechnology and manufacturing, NIST has identified the Center for Nanoscale Science and Technology as a top priority within the agency. It provides centralized access to NIST's unique

nanometrology facilities and nanofabrication resources, including the new Advanced Measurement Laboratory (AML), by researchers from industry, academia, and government. The CNST leverages the AML and broad metrology expertise across many disciplines at NIST to provide outstanding measurement capabilities for industry. By focusing on removing barriers to U.S. innovation in nanomanufacturing, the CNST directly addresses the R&D needed for this PCA and does so by converting science into technology for manufacturing.

Support nanomanufacturing via new investments in NIST activities to develop:

- New dimensional test standards with atomic precision capability and integrity and standards for autonomous atom assembly
- Optimized fabrication tools to manipulate and probe physical and chemical properties of materials at the nanoscale
- New intrinsic calibration systems for basic physical properties
- Methods for nanomanipulation of soft materials
- New, optimized high-resolution imaging and measurement methods for carbon nanotubes, fuel cells, and biological samples
- Improvements to fast, high-resolution positioning stage (154-picometer-resolution readout at rates of over 2 MHz)
- Tungsten nanotip electron emitters for higher-resolution electron microscopy
- Delivery of artifact standards for production metrology instruments, including linewidth, overlay, and 2D positioning

Additionally, emphasis is being placed on developing new metrologies in support of nanomanufacturing, including:

- Algorithms, devices, and systems to enable online process control of dimension and material composition
- Measurements of force dissemination for quantitative nanomechanical testing
- Novel fabrication platforms for testing functionality and operation of nanoimprint lithography, nanojet deposition, and other nanodevices
- A database of properties of atomic and molecular interactions among various materials to facilitate autonomous atom-by-atom assembly of nanostructures
- Measurements to assess functional and mechanical reliability of products during manufacturing

DOD: Guide and monitor the introduction of nanotechnology into military hardware; identify appropriate opportunities to introduce nanomanufacturing into the DOD SBIR, STTR, and MANTECH programs; enable the synthesis, generation, and assembly of individual nanostructures using lessons drawn from biology, including the use of viruses and related structures as templates for nanowires and for arrays of inorganic materials of particular interest; and develop affordable manufacturing approaches to nanostructured bulk materials.

It should be noted that Section 2 [of the NNI Supplement to the President's 2007 Budget] indicates zero DOD investment in PCA 5 because individual DOD research efforts addressing this PCA are primarily focused on other PCAs (i.e., PCA 2, Nanomaterials, and PCA 3, Nanoscale Devices and Systems). While numerous accomplishments in Nanomanufacturing have been made via defense research investments, and additional activities are underway as described above, these accomplishments have been made under research efforts aligned more closely with the objectives of another PCA.

DOE: Develop modular microlaboratories for collaborative work at the DOE Nanoscale Science Research Centers, such as the Center for Integrated Nanotechnologies' "discovery platforms," and other activities for the investigation of nanomanufacturability and related R&D on manufacturing processes.

EPA: Support development of nanotechnology-based process technologies that provide greener, more environmentally friendly manufacturing processes. Of particular interest are nanotechnologies that reduce the use and release of toxic pollutants, especially persistent, bioaccumulative toxics, hazardous air pollutants, and volatile organic compounds. Examples include nanostructured coatings for dry machining, metal-free nano-laminated coatings, and nanomaterials with smart characteristics, including reactive coatings that destroy or immobilize toxic compounds. Additional areas for support include R&D on high-surface-area nanomaterials for new coatings and environmental applications, and development of technology for solvent-free production of nanometer-size high-performance ceramic powders and similar materials.

NSF: Support R&D aimed at enabling scaled-up, reliable, cost-effective manufacturing of nanoscale materials, structures, devices, and systems, including novel concepts for high-rate synthesis and processing of nanostructures and nanosystems. Ultraminiaturized top-down processes and increasingly complex self-assembly (or other bottom-up) processes are being explored. Biosynthesis and bioprocessing methods will be developed for the manufacture of biochips and novel biomaterials, improved delivery of bioactive molecules, engineering of nanoscale sensory systems, and modification of existing biomolecular machines for new functions. Awards have been made through the Nanomanufacturing Program in the Directorate for Engineering, through other NSF core programs, and in response to the research and education theme in the NSF-wide program solicitation. In April 2006, NSF made an award to the University of Massachusetts, Amherst, for the establishment of a Center for Hierarchical Nanomanufacturing and expects this center to become fully operational in 2007.

UPDATE FOR FISCAL YEAR 2008

The following is excerpted from the NNI Supplement to the President's FY 2008 Budget**. This report was produced in a shorter, more concise, format than was the case for the 2007 report cited above. The following section on nanomanufacturing was included in the 2008 report under the heading, "changes in balance of NNI investments by PCA."

PCA 5: Nanomanufacturing

Across the NNI as a whole, increased spending on nanomanufacturing is expected in 2007 and 2008 compared to earlier years, with substantial increases over 2006, particularly at NIST and NSF.

- *DOD*: The variations in DOD funding for nanomanufacturing research are due to typical turnover within the programs and the changes in Congressional additions within the data (approximately \$2 million of the 2007 amount for this PCA).
- *DOE*: The Office of Energy Efficiency and Renewable Energy expects to increase its nanomanufacturing-related activities in 2008.

***The National Nanotechnology Initiative: Research and Development Leading to a Revolution in Technology and Industry. Supplement to the President's FY 2008 Budget* (Subcommittee on Nanoscale Science, Engineering, and Technology, Washington, D.C., July 2007; http://nano.gov/NNI_08Budget.pdf).

- *NIST*: Measurement science and standards at NIST in support of nanomanufacturing continues to be substantial and includes nanoparticle standards for improved characterization of manufactured products. Efforts focus on developing the technical and measurement infrastructure required by U.S. industry to translate potential nanotechnologies into manufacturable, market-ready products.
- *NSF*: A focus will be creating active nanostructures and complex nanosystems. This will include R&D and integration of ultra-miniaturized top-down processes, increasingly complex bottom-up or self-assembly processes, nanobiomanufacturing, and developing novel concepts for high-rate synthesis and processing of nanostructures and nanosystems.

APPENDIX D. BIBLIOGRAPHY AND LIST OF RELATED WORKSHOPS AND REPORTS

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M. C. Roco, Nanoscale science and engineering: Unifying and transforming tools, *AIChE J.* **50**(5), 890–7 (2004).

U.S. Congress, Public Law 108-153, 21st Century Nanotechnology Research and Development Act, (S. 189, December 3, 2003; http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=108_cong_public_laws&docid=f:publ153.108).

NANOMANUFACTURING WORKSHOPS AND REPORTS, 2002-2004

NNI workshops and related reports focused specifically on nanomanufacturing topics are listed below in chronological order by the date of the workshop:

- *NSF-EC Workshop on Nanomanufacturing and Processing*, Summary report of the workshop in San Juan, Puerto Rico, 5–7 January 2002 (NSF, 2002; http://www.nsf.gov/mps/dmr/nsfec_workshop_report.pdf).
- NSF Workshop on Grand Challenge in Manufacturing at the Nanoscale, Arlington, VA, 13 May 2002.
- Chemical Industry Vision2020 Technology Partnership and Energetics, Inc., *Chemical Industry R&D Roadmap for Nanomaterials by Design: From Fundamentals to Function*, publication following the June 2002 Vision 2020/NNI Grand Challenge Workshop (Vision2020, 2003; http://www.chemicalvision2020.org/pdfs/nano_roadmap.pdf).
- *NSF Workshop on Three-Dimensional Nanomanufacturing: Partnering with Industry*, final report of the workshop held in Birmingham, AL, 5–6 Jan. 2003 (Northeastern University, 2003; http://www.nano.neu.edu/NSF_Nano_Workshop_Report_final.pdf).

Complementary Workshops and Reports

Other complementary workshops and related reports that have been prepared or are to be finalized by the NSET Subcommittee and its members include the following, listed in chronological order by the date of the workshop:

- NSF Workshop: Small Businesses Move to Nanotechnology, Arlington, VA, 20–21 March 2002 (see workshop information at <http://www.nsf.gov/crssprgm/nano/activities/sbir.jsp>).
- *Nanotechnology Innovation for Chemical, Biological, Radiological, and Explosive (CBRE): Detection and Protection*, Report of the NNI workshop, 2–3 May 2002, Monterey, CA (World Technology Evaluation Center, Inc., Baltimore, MD, with the AVS Science and Technology Society, 2002; <http://www.wtec.org/nanoreports/cbre/index.html>).
- *Nanoscale Science and Engineering for Agriculture and Food Systems*, Report of the NNI workshop, Washington, D.C., 18–19 November 2002 (Cornell University and USDA/CSREES, 2003; <http://www.nseafs.cornell.edu/web.roadmap.pdf>).
- NNI Nanotechnology Grand Challenge in the Environment Workshop, Arlington, VA, 8–10 May 2003 (NSTC, Washington, D.C., 2007; http://nano.gov/NNI_Nanotechnology_and_the_Environment.pdf).

- NNI Grand Challenge Workshop on Nanostructured Materials by Design, Washington, D.C., 6–9 June 2003.
- *Buildings for Advanced Technology*, series of three NNI-sponsored workshops, held January 14–16, 2003 at the National Institute of Standards and Technology in Gaithersburg, Maryland; January 21–23, 2004 in Mesa, Arizona; and February 7–8, 2006 at Purdue University in West Lafayette, Indiana.
- *Nanobiotechnology*, Report of the NNI Workshop, Arlington, VA, 9–11 October 2003 (NSTC, Washington, D.C., 2005; http://nano.gov/nni_nanobiotechnology_rpt.pdf).
- *Nanotechnology: Societal Implications—Maximizing Benefits for Humanity*, Report of the NNI workshop, Arlington, VA, 2–3 December 2003 (NSTC, Washington, D.C., 2005; http://nano.gov/nni_societal_implications.pdf).
- *Nanotechnology Instrumentation and Metrology*, Report of the NNI workshop, Gaithersburg, MD, 27–29 January 2004 (NSTC, Washington, D.C., 2006; http://nano.gov/NNI_Instrumentation_Metrology_rpt.pdf).
- NNI Grand Challenge Workshop on Nanoelectronics, Photonics, and Magnetics, Washington, D.C., 25–26 February 2004.
- *Nanoscience Research for Energy Needs*, Report of the NNI Grand Challenge Workshop, Alexandria, VA, 16–18 March 2004 (2nd Ed., NSTC, Washington, D.C., 2005; http://nano.gov/nni_energy_rpt.pdf).
- *Nanotechnology in Space Exploration*, Report of the NNI workshop, Palo Alto, CA, 24–26 August 2004 (NSTC, Washington, D.C., 2004; http://www.nano.gov/nni_space_exploration_rpt.pdf).
- NNI Nanotechnology Research Directions II workshop, Washington, D.C., 8–9 September 2004.

APPENDIX E. GLOSSARY

2D	two-dimensional	CRCD	Combined Research-Curriculum Development (DOE program)
3D	three-dimensional	CSREES	Cooperative State Research, Education, and Extension Service (USDA)
AFM	atomic force microscopy	DARPA	Defense Advanced Research Projects Agency
AFRL/MLMR	Air Force Research Laboratory Materials and Manufacturing Directorate	DHHS	Department of Health and Human Services
AML	Advanced Measurement Laboratory (NIST)	DHS	Department of Homeland Security
ASME	American Society of Mechanical Engineers	DOC	Department of Commerce
ATP	Advanced Technology Program (NIST); also adenosine triphosphate (source of energy for physiological reactions)	DOD	Department of Defense
AVS	professional society: “Science and Technology of Materials, Interfaces, and Processing (formerly “American Vacuum Society”)	DOE	Department of Energy
AVS	professional society: “Science and Technology of Materials, Interfaces, and Processing (formerly “American Vacuum Society”)	DOEd	Department of Education
BIS	Bureau of Industry and Security (DOC)	DOL	Department of Labor
BIS	Bureau of Industry and Security (DOC)	DOT	Department of Transportation
CBAN	Collaborative Boards for Advancing Nanotechnology	DRAM	dynamic random access memory
CBAN	Collaborative Boards for Advancing Nanotechnology	e-beam	electron beam
C-C	carbon-carbon	EBL	electron beam (nano)lithography
CCR	Council for Chemical Research	EPA	Environmental Protection Agency
CDC	Center for Disease Control and Prevention	F1-ATPase	One of two domains of F-Type ATPase, a protein found in bacterial plasma membranes, mitochondrial inner membranes, and in chloroplast thylakoid membranes
CMOS	complementary metal oxide semiconductor		
CNT	carbon nanotube	FIB	focused ion beam
CNST	Center for Nanoscale Science and Technology (NIST)	FS	Forest Service (USDA)

Appendix E. Glossary

GMP	Good Manufacturing Practices	MRAM	Magnetic Random Access Memory
GMR	giant magnetoresistance	MURI	Multidisciplinary Research Program of the University Research Initiative (DOD)
GOALI	Grant Opportunities for Academic Liaison with Industry (NSF program)	MWNT	multiwall (carbon) nanotubes
IEEE	Institute of Electrical and Electronics Engineers, Inc.	NASA	National Aeronautics and Space Administration
ITC	International Trade Commission	NCMS	The National Center for Manufacturing Sciences, Inc.
ITIC	Intelligence Technology Innovation Center	NCNR	Center for Neutron Research (NIST)
IWGM	Interagency Working Group on Manufacturing Research and Development	NEMS	nanoelectromechanical systems
LIGA	“Lithographie, Galvanoformung und Abformung”—German acronym for lithography, electroplating, and molding—micromachining technology using X-ray lithography invented in Germany in the early 1980s	NIH	National Institutes of Health
LISA	lithographically induced self-assembly	NIL	nanoimprint lithography
MANTECH	Manufacturing Technology program (DOD)	NIOSH	National Institute for Occupational Safety and Health (DHHS/Centers for Disease Control and Prevention)
MBE	molecular beam epitaxy	NIST	National Institute of Standards and Technology
MEMS	microelectromechanical systems	NNCO	National Nanotechnology Coordination Office
MESA	Microsystems and Engineering Sciences Applications facility (Sandia National Labs)	NNI	National Nanotechnology Initiative
MMT	montmorillonite clays	NNIN	National Nanotechnology Infrastructure Network (NSF-funded network)
MOCVD	metal organic chemical vapor deposition	NNUN	National Nanofabrication Users Network (now NNIN)
MOU	Memorandum of Understanding	NRAM™	nonvolatile random access memory
		NRL	Naval Research Laboratory
		NSEC	Nanoscale Science and Engineering Center (NSF)

Appendix E. Glossary

NSET	Nanoscale Science, Engineering, and Technology Subcommittee of the NSTC	SIA	Semiconductor Industry Association
NSF	National Science Foundation	SINAM	(Center for) Scalable and Integrated Nano Manufacturing (NSF-funded center at University of California, Los Angeles)
NSTC	National Science and Technology Council	SME	small to medium enterprise
nTP	nanotransfer printing	SPC	statistical process control
OMB	Office of Management and Budget (Executive Office of the President)	SRAM	static random access memory
OSTP	Office of Science and Technology Policy (Executive Office of the President)	SRC	Semiconductor Research Association
P ² C	plasma pressure compaction	STM	scanning tunneling microscopy
PCA	Program Component Area	STTR	Small Business Technology Transfer Program
PCR	polymerase chain reaction	TA	Technology Administration (Department of Commerce)
PECVD	plasma enhanced chemical vapor deposition	TEM	transmission electron microscopy
PEM	proton exchange membrane	TFT	thin film transistor
PLD	pulsed laser deposition	TNF	tumor necrosis factor
PVA	polyvinyl alcohol	TPO	thermoplastic polyolefin
SBA	Small Business Administration	USDA	U.S. Department of Agriculture
SEM	scanning electron microscope	USPTO	U.S. Patent and Trade Office (DOC)
SBIR	Small Business Innovation Research Program	WTEC	World Technology Evaluation Center, Inc.
SFIL	step and flash imprint lithography		

National Science and Technology Council

Committee on Technology

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